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Solar Energy

Informatics Incorporated

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# SOLAR ENERGY

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This is a comprehensive review of present major developments and future planning in various fields of applied solar engineering. The study covers theoretical and experimental data on the background and state-of-the-art of applied solar research in general, with emphasis on foreign work, particularly in the Soviet Union.



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# INTRODUCTION

This is a comprehensive review of present major developments and future planning in various fields of applied solar engineering. The study covers theoretical and experimental data on the background and state-of-the-art of applied solar research in general, with emphasis on foreign work, particularly in the Soviet Union.

The extensive reference list indicates a broad spectrum of knowledge, experience and viewpoints on various aspects of solar engineering, as well as a growing interest in using solar energy for industrial and domestic purposes.

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# I

# GENERAL ASPECTS OF SOLAR ENERGY

Several surveys on recent and prospective world energy consumption indicate that it has been growing at an accelerating rate and is currently at a rate of somewhat more than 4 billion tons coal-equivalent per year for so-called conventional commercial energy sources alone. To this consumption should be added some 15 percent for "noncommercial" sources (agricultural waste, wood, etc.), which still comprise one-third to one-half of the total energy consumption in Latin America, Africa, and Asia. Long-range estimates of the world total consumption range between 15 and 20 billion tons coal-equivalent by the year 2000, and there is no doubt that energy consumption will grow much more rapidly than world population, which is expected approximately to double over the same period.

This acceleration is associated with expected economic development and rising national income. The relationship, however, is not simple as there are deviations due to such factors as differences in energy resources, climate, industrial structure, technical capabilities, transportation systems, and level of living conditions. Special attention therefore has to be drawn to different energy situations which could be divided into three categories with regard to power supply: the exceptional areas where a grid exists to connect power stations in industrial and urban centres with enough interconnected capacity to guarantee continuity of

supply within a limited area, often at a level comparable to that of developed countries; the areas where isolated power stations meet, at least in part, the most urgent power requirements; and the areas - which are the most numerous - where electricity is entirely lacking.

Broadly speaking, for areas in the first category, those with grid systems and developed energy supply, solar energy may be unimportant unless cost studies can show that it could provide power and other useful energy at competitive rates. In areas of the second category, characterized by high fuel and generating costs, solar power might well be a useful supplementary source effecting fuel savings. For many of the areas in the third category, which are by far the most typical in the underdeveloped countries and for which large-scale rural and village electrification cannot be foreseen in the near future, solar energy is the only source for power supply. It might become an important factor in improving living conditions and bring economic change by providing energy for telecommunications, conservation of perishable foodstuffs, water pumping and simple processing and manufacturing.

The aforesaid economic developments and industrial growth of the world have accelerated the interest in research and development of other power resources, among them solar energy. The widespread interest in solar energy utilization is seen in relevant activities in basic and applied research of numerous countries including Australia, Belgium, Brazil, Canada, Chile, the Federal Republic of Germany, France, India,

Israel, Italy, Japan, the Netherlands, New Zealand, Portugal, Spain, Sweden, Switzerland, the Union of Soviet Socialist Republics, the United Arab Republic, the United Kingdom, and the United States.

Solar energy arrives in the form of radiation which is harnessed in basic conversion processes classified into two general groups, utilizing either solar heat or light. The thermal processes may be classified according to the temperature obtained: low temperatures are the easiest to obtain by means of simple flat-plate collectors composed of plates coated with a black radiation absorbing substance which heats the water or any other medium used for the heat transfer; high temperatures require lenses or reflecting mirrors which capture the direct solar radiation and must have tracking equipment to keep them facing the latter. Low temperatures can be used for water and space heating or for seawater distillation; high temperatures are needed for driving engines, pumps or converting directly into electricity by thermoelectric generators without passing through a mechanical energy stage.

Solar radiation arriving in the form of light may be converted directly to electricity by means of photoelectric cells; it is most prominently utilized by nature in the photochemical process known as photosynthesis, the basis of all plant growth.

The average radiation emitted by the sun is known to reach the outer atmosphere at a rate of about two calories per square centimeter per minute, the value of the so-called solar constant. Hence, the total emission of the sun is about $2 \times 4 \times 22/7 \times (14,500,000,000,000)^2$ calories per minute. This radiation may be divided according to its spectral distribution into ultraviolet, visible, and near infrared; the latter two account for about 90 percent. The atmosphere distorts the solar radiation and alters the wavelength distribution; also the solar energy actually reaching the ground varies with latitude, season, time of day and other factors such as topography, meteorological elements, atmospheric dust and contamination. The solar radiation available on the ground is composed of beam or direct radiation (which is the only kind useful in a focusing collector), and diffused radiation, producing half of the available energy. There is also solar radiation reflected by the earth's surface, and long-wave reradiation such as nocturnal radiation which is particularly significant for some cooling purposes. The direct and diffused radiations may reach some 750 calories per square centimeter per day in sunny locations; it varies greatly and in any case is characterized by a low energy density. Taken at about one calorie per square meter per minute, an area of fifteen square feet is required to receive the heat equvalent of one kilowatt, and in practice a much larger area is necessary after actual conversion efficiencies and losses [3]. For example, the roof of a house with an area of 100 $m^2$ receives in 8 hours on a sunny day about 500,000 kilocalories. This is equivalent to burning of about 150 pounds of coal or 15 gallons of

gasoline. This amount of solar heat would give 58 kilowatthours of electricity using a boiler, engine, and dynamo system at a working efficiency of 10 percent [9].

Solar radiation falling annually on the world's land surface is estimated at about 28 times the world's total supply of fossil fuel energy, about 9 times the total supply of conventional nuclear energy, and about 11 percent of the total supply of breeder-reactor energy [1]. Total solar radiation reaching the earth's surface amounts to about $32 \times 10^{20}$ Btu per year based on 62.5 per cent transmission through the atmosphere. Present input to the world's human energy system is about $10^{17}$ Btu per year; hence 32,000 times as much energy falls on the earth as we are now utilizing. The direct harnessing of solar energy, therefore, appears to be an attractive proposition, but we still lack the complete knowledge to make effective use of solar energy. To use the sun effectively may require very expensive and extensive research [10].

Expressed in kilowatts, the average daily insolation, or primary radiation incident on the atmosphere, amounts to $178 \times 10^{12}$ kw (for a solar constant of 2 cal/$cm^2$ min) for the whole globe. This amounts to $1.5 \times 10^{18}$ kwhr/year. However, very little of this energy is available for use by man, as nearly a third of it is lost by reflection to space [11]. Of about $20 \times 10^{12}$ kw falling on dry land, only $1 \times 10^{9}$ kw has been utilized today [7].

The ocean also can serve as cost-free but low-temperature absorber of solar energy. In tropical regions, the ocean surface temperature may be up to 5° C above that of deeper water. This temperature difference can be utilized for the production of electricity [1], as discussed later.

In addition, fuel can be produced by direct solar radiation or from solar-derived energy. With an appropriate catalyst, solar radiation may decompose water to hydrogen and oxygen in a series of reactions, and hydrogen would be used as fuel in a fuel cell to produce electricity, or be burned to produce heat and electricity by standard means.

Solar cells deployed in space can produce electricity which would then be converted to microwaves, beamed to Earth, and reconverted into electricity. In this way, the solar radiation would be available almost 24 hours each day throughout the year. If feasible in the near future, eight large stations in space, each 13 square miles in size, would meet the United States mainland electric power needs in 1985, or more than 3 time its present requirements [1].

Such solar plants and complexes of the future require a great deal of work to develop large satellite solar collection and transmission systems, such as large sophisticated solar energy complexes which can produce not only solar power but also portable synthetic liquid fuels and lubricants.

In a plant such as this, concentrated solar beams (or better, microwaves of selected wavelengths) which are received continuously from a series of satellites will be separated into various beams, each of which, after further concentration and modification, will be directed to the process where they will be most useful: to a photoelectric plant to be converted directly to electric power, to a photochemical plant for the production of chemicals (to store solar energy of for the other use), to solar furnaces or solar ponds for the production of heat for processing purposes, and other more specific purposes such as the dissociation of water (with the aid of a catalyst not yet discovered) to produce hydrogen and oxygen, which can be used as fuel for fuel cells or as raw materials for the manufacture of fertilizers, synthetic hydrocarbons and chemicals such as rubber, plastics, fibers, solvents, etc. (Fig. 1).

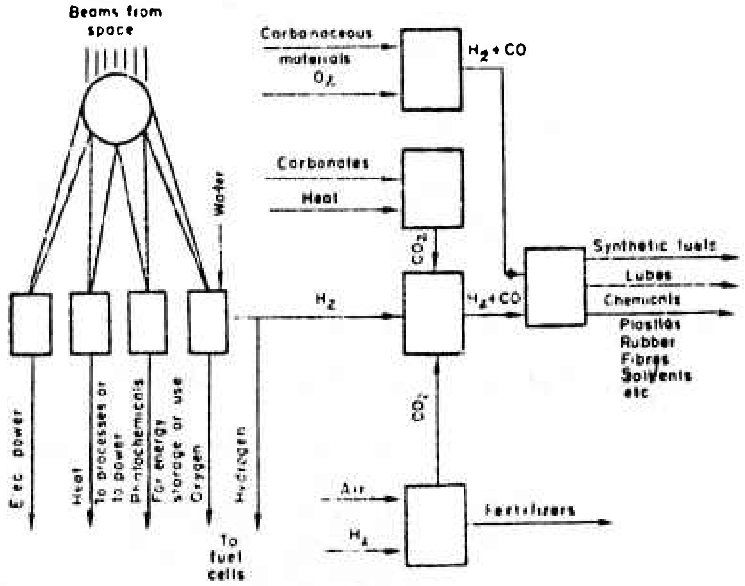


Fig. 1. Solar energy complex [51].

In a complex such as this, the hydrogenation of carbon monoxide, a process that is already well known, can be used to produce hydrocarbons and chemicals similar to those that we use today. The hydrogen and carbon monoxide that are required to do this can be obtained by the partial oxidation of carbonaceous materials, by the dissociation of carbonates, or in the extreme, by the extraction of carbon dioxide from the atmosphere to be reacted with hydrogen obtained through the dissociation of water. The ultimate step in "recycling" would be when the $CO_2$ and the water that are produced in combustion are recycled back to produce more fuel [51].

Solar cells can be deployed on earth to produce electricity but for limited periods of daylight only. Energy storage is required to provide power during periods of darkness or inclement weather. It is estimated that an area of solar cells having 100 x 100 miles surface in the southwestern desert could supply all the United States electrical needs for 1985.

A variety of methods for generating fuel from solar energy are illustrated in Fig. 2. Plants can be grown, harvested, and processed either for direct burning, converted by pyrolysis or biochemical means

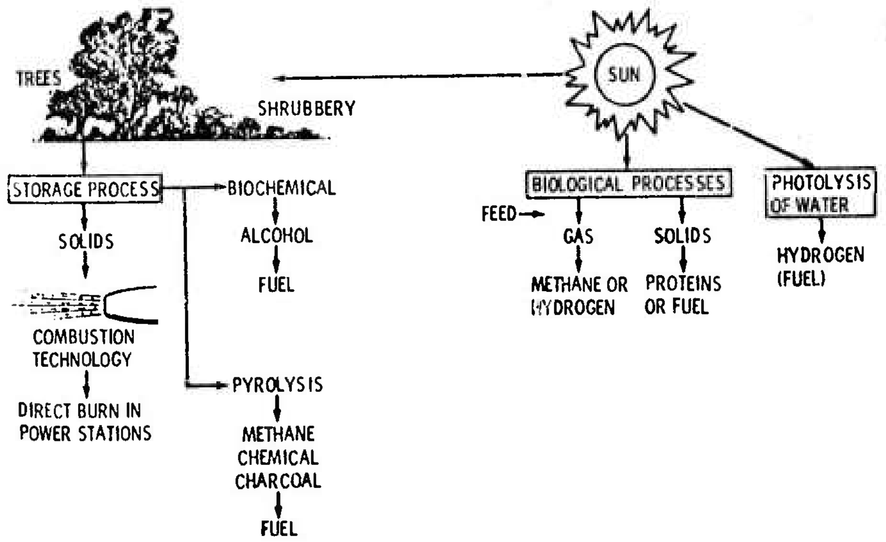


Fig. 2. Diagram of clean renewable fuel from solar energy [1].

into gaseous, liquid, or solid fuels. Metallic ions can catalyze the breakdown of water in a series of reactions to release the potential fuel - hydrogen; the solar radiation provides the energy needed for this process. Microorganisms such as bacteria and algae can be grown with the aid of solar radiation, and nutrients with hydrogen and methane (byproducts of these growth processes) represent a potential fuel [1].

With the exception of solar water heating, most possible applications of solar energy are still in the experimental and development stage and need further research in laboratories, pilot projects and field trials [3]. With an economical and practicable technology to collect, store,

convert, transmit, and supply energy, solar radiation is considered as the most clean energy source [1].

It has been estimated that with adequate research and development support, by the year 2020 solar energy could provide at least 35% of the heating and cooling, more than 30% of the methane and hydrogen needed for gaseous fuels, and eventually more than 20% of the electrical power needs of the U.S.A. [24].

By virtue of its very nature of being a "new" source, it may be noted that solar energy contributes only an insignificant share to the total world energy production today. In industrialized countries, solar energy can be utilized for solar furnaces (for high-temperature research), solar power in space vehicles, and water and space heating. However, solar energy is likely to find its most important utilization in less developed countries, where solar energy in the near future will be a supplementary rather than a competitive source of energy, particularly in areas with favorable availability of solar energy, i.e. in the belt between latitudes 40° N and 40° S, in which most of the underdeveloped countries are located and are lacking conventional energy [3]. However, latitudes up to 50° N and 50° S are by no means ruled out completely.

In conclusion, recent investigations carried out in several countries have shown the possibility of utilizing solar energy in the near future much more widely and in different ways even with the present stage

of technical possibilities [23]. At the present state-of-the-art, a solar plant for the production of electric energy would cost about three times more than conventional power, but as the cost goes up for nuclear, coal and gas systems, solar energy is bound to become more competitive. If sufficient research and development funds were provided, solar energy could become a viable economic alternative within 10 to 15 years.

# II

# FOREIGN SOLAR ENERGY RESEARCH AND ENGINEERING

A. Historical Background

Since ancient times man has striven to utilize solar energy. Archimedes seems to have been one of the first pioneers in the practical application of solar energy. According to the Creek historian Galen (130-220 A.D.) Archimedes succeeded in setting fire to Roman warships by means of a "burning mirror" [20]; Archimedes established the fact that the focus of a spherical mirror is in the middle of its radius.

Euclid in his works "Optics" and "Cotoptics" attacked the problems of geometrical optics, and like Plato, supported the theory of optical rays. He was the first to formulate the basic law of geometrical optics, the rectilinear propagation of light, and the reflection law from plane and spherical mirrors. In the early medieval periods, scientists of Central Asia emphasized the capability of a lens to concentrate light. The Arabian scientist Ibn Haisam Alhazen (965-1039), investigating plane, cylindrical, spherical and conical (convex and concave) mirrors, discovered that in a more dense medium the refracted ray draws near the normal.

Almost eighteen hundred years elapsed before a physicist took up where Archimedes left off. Athanasius Kircher (1601-1680), the first to repeat the Greek scientist's experiments with the burning mirror, had a more peaceful application in mind than the burning of ships; his

efforts were directed at setting fire to a woodpile from a distance. Both Kircher's and Archimedes' methods for utilizing solar radiation are basically the same as those employed today; the burning mirror is still the simplest and most popular means of putting the sun's rays to work [20].

The first water distillation plant was built in Chile in 1872 [5], and in the late 19th and early 20th century, construction began of various solar installations utilizing advanced technology.

A more detailed chronology of all the world's pioneers in solar energy and their inventions is omitted as beyond the scope of this study, except for a brief tabulation of Soviet research and developments. More detailed technical data on design and operation characteristics of various installations mentioned here as utilizing solar energy are provided in Chapters III and IV.

In prerevolutionary Russia, solar engineering was rudimentary. Starting with research by M. V. Lomonosov, G. V. Rikhman and others, this period produced 19 works in the fields of solar engineering, among them an atlas on solar radiation; several works on prospective utilization of solar energy; and experimental research on a solar oven designed in 1909 by V. K. Tserasskiy, considered at that time as the energy generator of the future.

After the revolution, industrialization of the Soviet Union led several leading scientists to study assimilation of solar radiation as a potential source of energy. Since then, intensive research has produced many technical studies on diverse solar engineering subjects in the U.S.S.R.

Over the last 15-20 years a notable increase in Soviet solar research has occurred, especially on the concentration of solar radiation, new film characteristics, development of energy installation components primarily of thermoelectric, photoelectric, and thermoemission converters [6].

V. N. Bukhman, one of the pioneers of Soviet experimental solar engineering, in 1926 constructed a solar oven with step-type facetted mirrors at Zaysan, Kazakh SSR. He successfully applied this invention for medical treatment of skin, ulcer, and internal diseases by irradiation pulses of concentrated solar rays [6, 26, 31].

At Yangiyul', near the city of Tashkent, Uzbek SSR, nine types of experimental greenhouses for a cotton farm were constructed in 1932 [6, 26].

In 1930 permanent scientific-technical solar associations were created in Moscow, Tashkent, Samarkand, Ashkhabad, Alma-Ata and in other cities, and in 1931 the Soviet Central Asia Heliotechnical

Institute was established at Samarkand [31].

During the 1930-1938 period, several problems were solved, such as solar light penetration in greenhouses, heat loss on vertical glass plates, theory of light fields and energy transfer in a scattering medium. Until 1940, several institutes and plants in Leningrad were active in applied solar research, using the Turkmen SSR as a testing ground for various solar water heaters boilers, water distillers, cooking ovens, and refrigerating installations. Several laboratories conducted research to establish the value of heat and mass transfer coefficients for hot water between 18 and 100° C, through a steam-air mixture on the surface of a condenser by utilizing simple pan-type distillers and multi-unit atmospheric pressure heat exchange tanks [6].

In March 1934, the first Solar Engineering Laboratory at Tashkent, Uzbek SSR, was organized for research and design of solar heaters, fruit dryers, water distillers, silkworm cocoon processors and dryers, and fusion of sulfur by solar rays. In 1943, this laboratory was reorganized into the Physicotechnical Institute of the Uzbek Academy of Sciences. This Institute has been engaged in a variety of research in the fields of theoretical and applied physics. A semiconductor battery for direct conversion of solar into electrical energy has been developed, and a solar furnace 15 to 20 m in diameter was designed for studying heat-resistant alloys and ceramics at high temperatures. Research was conducted for the Soviet silk industry on the killing of silkworm pupae and preservation of silkworm cocoons with gamma rays. In 1946, the

Division of Theoretical Physics was formed as an independent unit within the Institute, and in 1948, the Laboratory of Cosmic Rays was organized to study the interaction of cosmic rays with matter.

In 1959, the Solar Laboratory was created within the Institute to conduct research on conversion of solar into electric energy, developing and testing of solar concentrators, and application of new materials in solar engineering. Considerable research has been conducted here on the discharge capacity of a silicon photobattery, commutation of photoconverters, characteristics of large light flux photoelements, etc.

In 1963, the Solar Laboratory was the basis for organizing the Solar Physics Department with four laboratories. Among its assignments were the design of solar furnaces for high-temperature research, development of converters based on thermoelectric generators and gas-piston pumps principles, design of various types of concentrators, etc. [26].

The Heliotechnical Laboratory at Tashkent has turned out precision reflectors for welding, solar cookers the equivalent of a six-hundred-watt hot plate, and a solar boiler that folds up compactly into a suitcase. Water heaters of all sizes were developed and used. The most ambitious was a large heater in Tashkent, which boiled 500 liters of water daily, and a solar boiler producing 130 kilograms of ice a day [97].

To illustrate the world-wide scope of interest in solar research and developments, the following are some major achievements by other countries in various fields of solar engineering.

Israeli scientists have been doing some of the most interesting work in the solar field. The National Physical Laboratory of Israel has produced five-horsepower turbines "fueled" by inflated plastic reflectors, highly efficient heat absorbers for use in heaters and power plants using solar energy, and a promising idea called the "solar pond", treated chemically to store the heat of the sun. The Israel Institute of Technology has developed water heaters, coolers, stills, and dryers. The leading solar energy product of Israel is the "Miromit" solar water heater, a unit so efficient that the country's electric utilities were forced to drop their prices to compete; the first time that solar energy had been economically competitive with conventional power. They have been produced at the rate of four thousand a year, and sold in Israel and four other countries. Israeli scientists are also doing work on "selective surface" heat absorbers, by developing the most efficient blackened collectors known for trapping solar heat, capable of storing from 80 to 90 percent of the heat incident on them.

The Japanese have been active proponents of solar energy. The Kobayashi Institute of Physical Research in Tokyo and the Government Industrial Research Institute in Nagoya are two centers of activity. Japan is progressive in electronics, and her scientists have invented such advanced

semiconductor devices as the tunnel diode; it is not surprising to find production of solar batteries among their accomplishments. These were put to practical use in remote radio installations and in lighthouses, where they function for long periods with little maintenance. Solar water heaters are being mass produced, with more used there than in the rest of the world combined. By 1960 there were 250,000 in use, with an estimated annual saving in coal of one ton per heater, and with heaters ranging in price from nine to eighty dollars. Solar cookers are also produced in a variety of shapes, and there are industrial and research solar furnaces in operation. A more unusual solar energy application is the growth of algae in plastic tanks. The Japanese, critically short of food, have done more work in this direction than any other country, even producing chlorella food supplement powders commercially. An acre of pond has produced about twelve tons of algae yearly. Other research and development projects range from the use of solar heat to distill sugar-cane juice to the heating and cooling of residences [97]. The Japanese Association for Applied Solar Energy was established in April 1961 to promote fundamental and applied research in the application of solar energy. It now has about eighteen supporting organizations and eighty individual members. The Japanese section of the International Solar Energy Society was started in 1971 [101].

France has continued its leadership in the furnace field. The big thirty-five-foot solar furnace at Mont Louis remains the largest in the world, and surely the most active and productive, since it has operated continually both for research and industrial smelting. Another huge furnace at Odeillo has an output of one thousand kilowatts, making it the

first solar installation in the megawatt range.

Algeria has been active in solar energy research perhaps as a defensive gesture, since much of her territory lies in the Sahara Desert. One logical goal was the air-conditioning of desert houses using solar heat. The third largest solar furnace in the world, located at Bouzareah, is used for photochemical research and for producing nitrogen from the atmosphere. Also under study are selective thermoelectric surfaces and solar batteries. "Radiosol" water heaters are produced commercially.

Australia has developed a twelve-foot solar furnace on the Kensington Campus of the University of New South Wales. The furnace develops about five kilowatts of heat, and reaches temperatures more than 3,300$^{o}$ K. Production of salt from sea water is another solar energy application, and experiments have been made on spraying brine through the air to speed evaporation.

Burma has built low-cost cookers, heaters, and stills, and experimented with the use of solar energy in salting fish. Scientists suggest that a solar-powered refrigerator would be of more value to the Burmese than a cooker.

Canada has built a solar-heated house, despite its northerly location. In search of a warmer climate for its solar researchers, McGill University has opened the Brace Experiment Station in Barbados, West Indies.

Ceylon has also researched the use of solar energy for refrigeration. In 1955 scientists there performed a valuable service by measuring solar radiation during an eclipse.

Chile was the scene of large solar stills in the last century, and engineers have again proposed such installations; considerable research has been done on heaters, cookers, furnaces, and solar batteries.

Both Nationalist and Mainland China are active in the solar energy field. On Taiwan the population had doubled since 1946, and estimates are that local fuel resources would last only another forty years at present rates of consumption. Therefore, work is being done at Taiwan Normal University to produce cookers, space heaters, water heaters, and furnaces for island use to save conventional fuels. On the mainland, it has been reported that about eighty factories, mostly in Shanghai, were turning out heaters and cookers.

Egyptian scientists are investigating sea water distillation, solar heating, drying, baking, pumping, etc.

England, though quite far north, has done a fair amount of solar research. Many of its scientists were pessimistic about the possibilities, but worked on early models of a revolutionary hot-air engine that could run on solar energy.

Germany has had a few exponents of solar energy actively experimenting with solar heating, cooling, drying, and even extracting drinking water from the air with solar energy. As early as 1935 a solar refrigerator was built and tested in the Negev Desert. Some algae culture research had also been done.

India has excellent solar scientists, and has developed practical solar cookers, stills, and heaters. With the National Physical Laboratory at New Delhi as headquarters, work is progressing on solar refrigerators and solar power plants for villages.

Italy has built water heaters and space heaters, among other projects, and residential installations of water heaters have been made. The University of Bani is a research center.

Lebanon has perfected a collapsible solar cooker.

South Africa is conducting research on space heating, water heating, stills, and solar furnaces.

Spain has formed a "Special Energy Commission" to carry out work in solar energy research.

Switzerland is manufacturing and marketing solar powered clocks to bring the ancient sundial concept of time from the sun up to date.

The United Nations had long been interested in the development of solar energy, particularly with respect to applications in the underdeveloped lands of the world. In 1961 the U. N. sponsored the United Nations Conference on New Sources of Energy in Rome. Representatives of some sixty countries were on hand to hear papers by specialists in thirty countries on the use of solar energy, wind power, and geothermal power. Solar energy was a main concern of the conference, and of particular interest were the revolutionary Battelle Institute Stirling-cycle solar engine and the five-horsepower solar turbine from Israel [97].

## B. Research Trends

Solar energy, with reference to achievements and practical experience demonstrated in various countries, holds out the promise of contributing to energy supply and economic growth, especially in the less developed countries. However, scientific and technological research are essential to accelerate the use of solar energy in various fields of industrial and domestic life. The technological level of most solar applications is at an early stage of development and more basic and applied research are needed for these applications, especially for solving the difficult problem of energy storage and its conversion.

There is great need for much closer coordination of research activities and more efficient utilization of technical manpower active in solar research in assisting less developed countries toward developing various fields of solar energy.

Most solar applications are now in the experimental or pilot stage. There are some cases reaching a commercial scale, but further efforts in research are needed to achieve widespread practical use under realistic and economical ranges of operation. These efforts demand broader national and international cooperation in basic and applied research [3].

In the Soviet Union since 1972 the Physicotechnical Institute and the Microbiological Section of the Electronics Institute of the Uzbek Academy of Sciences, as well as the Bukhara and Karshi Pedagogical Institutes, have been studying problems on solar energy utilization. Coordination of all such work in solar engineering is carried out by the Council on Solar Engineering Problems of Presidium of the Uzbek Academy. The Physicotechnical Institute is active in the following major subject areas:

o research of optical systems to concentrate solar energy for electricity and technological purposes;

o development of gas-piston dynamic converters of solar energy;

o production of efficient solar heaters, cookers, distillers, dryers, accumulators and airconditioners;

o research of high-temperature physical processes utilizing solar or radiation furnaces with simulated solar radiation.

For utilization of solar energy, the Physics Department of Bukhara Pedagogical Institute is testing experimental water distillation models, solar air conditioners, and concentrators of light flux impulses for cotton seed irradiation; the Karshi Pedagogical Institute is experimenting on greenhouses with accumulated solar energy through a closed moisture cycle or film cover.

The Microbiology Section of the Uzbek Academy, jointly with the Physicotechnical Institute, is investigating methods to increase chlorella yield, a valuable animal fodder, by means of concentrated solar light.

Since 1972, the Academy's Electronics Institute has been conducting high-temperature research using two universal solar furnaces, each composed of two parabolic concentrators with horizontal and vertical optical axes respectively, and heliostats alternately served by the concentrators.

The Renewable Energy Sources Section of the Scientific - Technical Experts Commission, State Scientific Council for the Energy and Electrification Committee, Council of Ministers USSR, has recommended extensive utilization of the Physicotechnical Institute products, including solar heater components made of curved profile thin-leaf steel, solar distillers of the greenhousing type, portable plastic stills, installations for seed irradiation, and solar cookers.

To fulfill the above program, it was decided in 1972 to build an industrial plant in the Bukhara District for the production of heliotechnical devices with an annual production capacity of 25,000 solar cookers and 50,000 $m^2$ of water heater elements [26].

The Solar Engineering Laboratory, built in 1950, has produced precision reflectors for welding and cookers. Water heaters of many sizes have been developed and are very popular.

While their progress with large rural power installations remains slow, the Soviets are progressing with newer and more sophisticated solar conversion techniques. Utilizing a six-foot mirror for focusing the heat onto a semiconductor thermoelectric generator, the Soviets claim a unit producing one horsepower output [21].

Broad prospects of high-temperature processing with solar furnaces have also attracted the attention of Ukrainian material scientists, who are utilizing several parabolic concentrators for welding, refining, synthesis, and physico-chemical characteristics studies of refractory materials [31].

In the Moldavian SSR an extensive research program on biological photoenergetics is underway since 1972. It has been ascertained that the irradiation of winter cereal seedlings causes considerable changes in the composition and content of free amino acid, favorably affecting the growth process and increasing the crop yield [31].

Leading Soviet solar scientists consider the production of mechanical and electrical power of large capacity as the basic problem in solar engineering, since small steam-piston or turbine motors have low

efficiencies (not over 2-3%) and, consequently, ineffective output. Therefore, their development of solar energy resources is being directed toward the construction of stations with not less than 1500 kw capacity. One such station, of 1500-2500 kw capacity, and scheduled for the Ararat valley in the Armenian SSR, is being designed by the Power Engineering Institute im. G. M. Krzhizhanovskiy of the Academy of Sciences [30]. The same Institute announced that it has designed and built a solar mirror system capable of amplifying the incident solar energy from 20 to 10,000 times. Whether the Soviets are planning to use lasers in the Ararat valley project is not known, but some form of solar amplification will doubtless be used [20].

The Low Temperatures Laboratory of the Physicotechnical Institute and the Odessa Technological Institute of the Food and Refrigeration Industry have been conducting research on space air conditioning since 1972. Based on this, the Institute of Technical Thermophysics of the Ukrainian Academy of Sciences, on a technical assignment from the Laboratory, in 1972 designed an experimental commercial solar absorption refrigerating plant and has completed an experimental model [32].

To summarize research trends briefly, we may examine a few of the many important problems in solar research and development that must be pursued in order to cope with solar complexes such as that shown in Fig. 1.

In general, as such solar complexes will be located in large uninhabited areas of the world, we must learn how to transmit electrical energy over long distances more effectively, perhaps without wires.

We should also effect improvements in heat pumps so that these can be used to supplement the sun for the heating and air conditioning of homes and other buildings. Also much more work is needed on the study of photochemical reactions, in which may lie the solution to the problem of storing solar energy.

We should continue the improvement of solar cells and thermoelectric and thermionic devices for the direct conversion of solar energy to electricity. We need to improve the methods and the cost of producing, storing, and transporting hydrogen and oxygen so that these can be used in fuel cells in homes and also in the manufacture of chemicals and synthetic liquid fuels.

In addition, a great deal of work needs to be done on the development of large satellite solar collectors and concentrators, and on the devices that must be used to convert the solar spectrum to wavelengths that can be transmitted to earth most effectively. The collectors may be composed of solar cells which can be coupled directly to DC to microwave

converters. Alternatively, the collectors may be simple mirror-like parabaloid devices focused on laser-like converters or on a conversion system consisting of a dynamic Rankine-type generator coupled to klystron-type converters.

Work directed toward systems such as these will be extremely expensive and obviously cannot be expected to be supported through profit motivation alone. It simply must be supported by the governments of the world, just as atomic energy was.

The problem before us today, therefore, is to promote awareness as to the ultimate need for solar energy, and to enlist the assistance of those who are in a position to allocate funds and facilities for the support of research in this field [51].

C. Prospecting, Data Collecting, and Forecasting

Prospecting and data collection represent the starting points for selecting the sites for various installations utilizing solar energy. As far as physical availability is concerned, general data collection should be part of the normal assignment for the meteorological services. In general, the gaps in meteorological data collection are gradually being filled by the expansion of the meteorological station networks, except in some arid zones and microclimatic areas which are the most appropriate

for solar energy utilization. The purpose of data collection and analysis is to gather information on different types of radiation, spectral distribution, total and mean daily, monthly, seasonal and annual variations, incidence of low radiation, and other adverse factors such as rain, wind, dust, clouds, temperature etc.

The World Meteorological Organization (WMO) is interested in promoting meteorological research and training related to solar radiation and in assisting scientists in utilizing meteorological data and knowledge. Various working groups, under the WMO Commission for Instruments and Methods of Observation (CIMO) and the Radiation Commission of the International Association of Meteorology and Atmospheric Physics, are very active in solar radiation measurements [3].

Knowledge of solar radiation is clearly necessary for the design of efficient and economic devices for the utilization of solar energy. Nevertheless, the study of global solar radiation has lagged far behind that of other meteorological elements, especially in the less developed parts of the world where few radiation stations are in operation. Among several aspects of radiation climatology, the three basic areas which require considerable study are ways in which estimates may be used to supplement needed observations in countries with inadequate radiation records; the number of years of observations needed to establish reliable mean values of global radiation; and the frequency of periods of low radiation [33].

The Russian Atlas of the Global Heat Balance, published in 1963 by M. I. Budyko, and Distribution of Solar Radiation of the Continents (Fig. 3), based on data from 2100 observation stations and published in 1961 by T. G. Berlyand, represent valuable contributions to solar engineering.

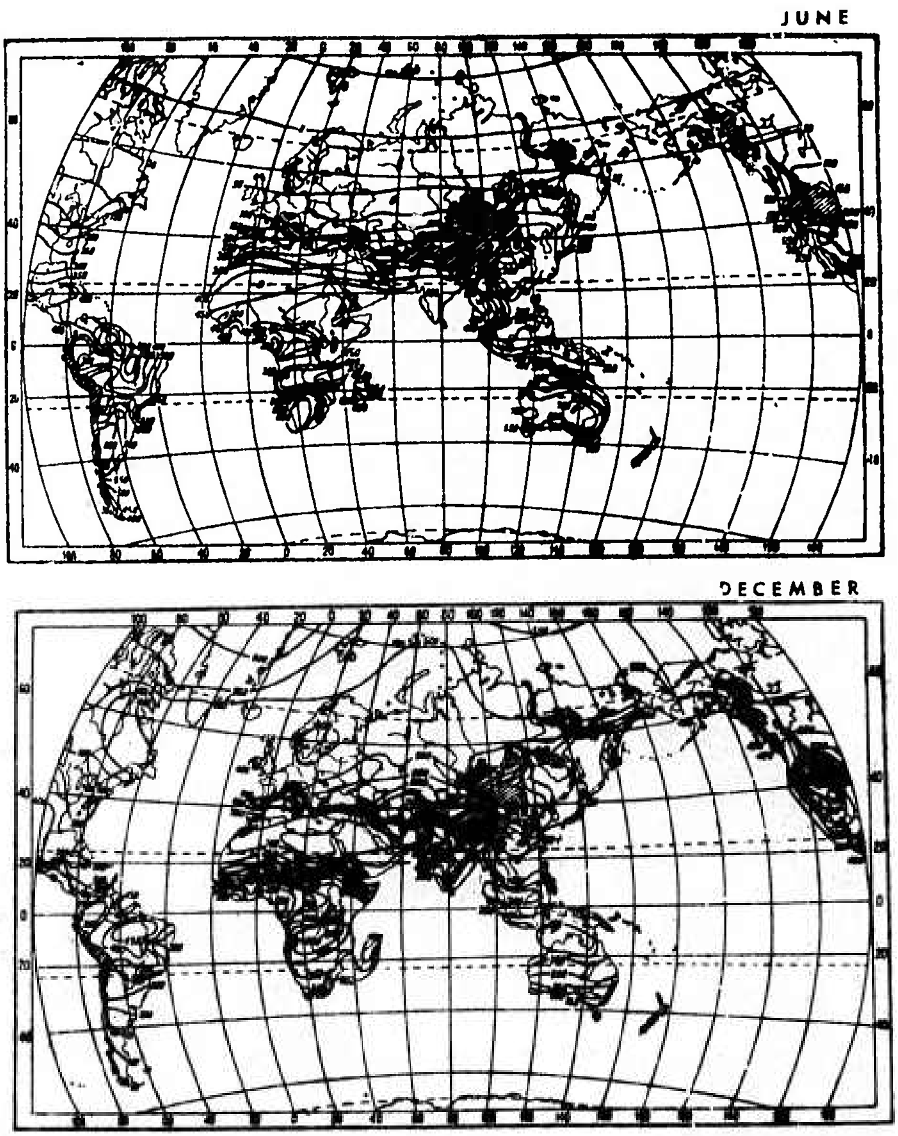


Fig. 3. Total solar radiation, cal/cm$^2$/daily.

In 1968, the Soviets published a comprehensive study on the diurnal, monthly and seasonal atmospheric transparency coefficient for direct solar radiation. This study is based on data compilation from many years obtained from 175 actinometric stations [35].

Although there are now published records of global radiation for well over 400 stations, concentrated principally in North America and Europe, relatively few networks are maintained in other countries. In Africa there are some 25 stations south of or on the equator, and 6 stations north of the equator, the whole continent thus being covered by only about 31 stations. In Australia, where utilization of solar power could be extremely valuable, there are only 10 stations. The only records for China and southeast Asia are for recently established stations in Singapore and Hong Kong, and a long established station at Macao.

In the Soviet Union there are about 5000 meteorological stations collecting, besides various hydrometeorological data, diurnal air temperatures which can assist in the study of solar radiation. These data are published in the Climatological Yearbooks and cover 5-10 year periods over various geographic areas.

In recent years, however, and particularly under the influence of the I.G.Y., a number of new networks have been established in several countries. Necessary background information for the utilization of solar energy in the less developed countries is still not complete and

available; however, it is possible to obtain estimates of radiation derived either on theoretical grounds or from a relationship with known meteorological parameters, such as the duration of sunshine or cloudiness. Such estimates have been used to compose three sets of monthly charts for the world and for a number of regional surveys covering Canada, the United States, Finland, the Soviet Union, New Zealand, and Northern Africa [33].

In many cases very little information is available on sunshine period recordings. There are several methods to establish correlation of solar radiation with reported cloud cover. However, some methods of cloud classification have been examined and in no case has a high correlation coefficient been found. It is concluded that if cloud reports are used to predict the values of solar radiation, only monthly or longer averages may be obtained with reasonable accuracy [39]. Meanwhile efforts are continuing to find out more regarding the characteristics of solar radiation both in outer space and on the surface of the Earth [20].

D. Standardization and Pilot Stations

Standardization of solar measurements, instruments, and equipment will be essential for adapting this new energy technology toward decreasing cost, increasing the exchange of data, and to provide uniform training and testing of instruments and equipment. The standardization

of equipment could bring economic benefits from mass production, interchangeability of parts, comparability of performance, and would accelerate the utilization of solar energy.

There is great concern for establishing the pilot stations and experimental centers in less developed and energy-poor countries favored with plentiful sunshine. These activities would serve as distributors of solar measuring instruments, disseminate information regarding site selection and equipment, adapt equipment to local need, and contribute to the clarification and solution of technical problems under various conditions of operation. In addition, the pilot stations and experimental centers would increase exchange of research personnel, promulgate technical advances, and provide advisory services. They could demonstrate possibilities of savings and act as intermediaries for technical and financial assistance. They could also innovate actual applications under the conditions prevailing in less developed countries, by providing a better understanding of the social and economic problems connected with the introduction and maintenance of new solar energy applications, such as solar cookers, ice-making machines, water pumping and other power operations for the individual household or village level.

The proposed pilot stations and experimental centers are regarded as a vital means of breakthrough in the application stage, and represent a practical approach in well selected areas in the different

regions of the world. Besides national efforts and international cooperation, the United Nations and its specialized agencies under the Expanded Program of Technical Assistance and the Special Fund could provide great assistance [3].

The need for the creation of pilot stations or research centers has been stressed at various national and international meetings, as well as in the technical literature. These will assist in the standardization and exchange of technical data pertinent to the research procedure and results, cost of construction, modes of operation, and maintenance and efficiency of various solar engineering installations.

There is a proposal, outstanding since 1971, for the creation of an International Solar Engineering Research Center which could be operated in Greece under the supervision of the Desalination Department of the Hellenic Industrial Development Bank, and with aid of the International Solar Energy Society. The basic purpose of the Center would be to provide an environment where stills developed in various countries could be tested under identical conditions, to evaluate the experiences gained in various countries. It is believed that this Center will provide more adequate comparison of existing installations, general evaluation of structural and operational data, planning of new installations, and direct future research and development for more economical utilization of solar energy for distillation and desalination [8].

In view of the great importance of salt flats as solar heat collectors (see Chapter III) it has been proposed to create an Institute of Arid Zones with headquarters at Antofagasta, Chile, with the contribution of investigators from three involved countries - Argentina, Bolivia, and Chile. It is proposed that this institute could be more easily organized and financed by OAS or UNESCO since both possess the necessary experience [25].

To make the possibilities of solar energy known, a broad educational program will be indispensable; news items about novel designs in solar engineering are insufficient to incorporate these new methods in the way of life of a people. The basic ideas about solar energy should be included in the curricula of scientific and technical secondary education, of vocational building and trades schools, and of schools of architecture and municipal planning [66].

# III

# SOLAR ENERGY COLLECTION, STORAGE AND CONVERSION

A. General

Contemporary solar engineering in its concern with the collection, storage and conversion of solar energy for industrial, agricultural and domestic use, is focused on the following major problems:

- o conversion of solar into electric and mechanical energy,
- o generation of high temperatures,
- o development of low-temperature equipments (water heaters, solar cookers, dryers, hothouses, water stills, etc.),
- o cosmic heliotechnology,
- o composition and distribution of solar radiation over the globe,
- o conversion of solar into chemical energy,
- o photosynthesis of biological substances, and
- o medical-sanitary heliotechnology [29].

The possibility of power generation with solar energy is one of the most important goals in solar engineering, especially the potential key role of small power units which could find great application in telecommunication, lighting, pumping and many other purposes for the less-developed areas lacking conventional power. There are two approaches

in solar power generation: heat engines more or less of conventional types operating on energy from solar collectors, or direct conversion to electricity through different devices. These types are discussed in more detail in Section C of this chapter.

Although the production of mechanical and electric power through solar heat engines has long been a goal and many models have been built over the years, little use has been made of solar energy for such power generation. In a notable exception, Israeli scientists have developed a small solar-powered electric generating plant in the 2-10 kilowatt range which incorporates a new turbine operating on organic vapor at unusually high efficiency, a novel type of balloon-like plastic mirror collector, and a heat storage system allowing night operation at reduced load (see Section C).

Another promising technology and a novel type of heating system introduces the solar pond as collector of solar energy. Though in an early stage of development, this might bring solar power to the megawatt scale at a cost comparable with that of large conventional plants. Another type of heating system considered in the turbine and piston category is one which suggests a new use of solar energy in the so-called Stirling (or closed-cycle regenerative gas) engine.

The intermittence of supply has been repeatedly noted as perhaps the most serious limitation to the practical utilization of solar energy for various power purposes. Except where the intermittence does not greatly matter, as in water pumping for irrigation, this limitation

may have to be overcome before proper application of equipment can be found for continuous supply; this means finding an economical way of storing the solar energy. However, it is impossible to store raw solar energy as such for subsequent conversion to electricity. The closest form would be storage of heat, but this would require a high degree of insulation for high temperature heat. The most familiar method is the use of electric storage batteries useful for small power purposes. Unfortunately, they have insignificant economic potential and have not been the subject of any recent technological breakthrough that could promise a really drastic reduction in cost.

Most promising are the considerable achievements in fuel cells, which may be divided into two types based on electrolysis and thermal regeneration.

In the first category are the hydrogen-oxygen cell systems, in which electricity is used to electrolyze water or other chemicals into hydrogen and oxygen, then stored separately. The two gases may subsequently be recombined to produce electricity in a fuel cell, which has the advantages of no moving parts and high efficiency. However, the electrolyzer and the generating cell have not so far been combined into one unit. Although certain problems remain to be solved, fuel cells in this category may become highly significant, particularly with reduction in their cost.

Thermally regenerative fuel cells or thermally reversible galvanic cells are based on a closed cycle and recharged by heat rather than by external electric current. They combine in one device: electric generation, regeneration (or separation of lithium hydride or other chemicals for later recombination and power generation), and storage. Although still in an early experimental stage, they may find significant application in conjunction with highly concentrated solar radiation providing the heat.

Other solar energy research is seeking to find solutions through photochemical conversion and storage, including photolysis rather than electrolysis for separation. If successful, these processes would also solve the storage problem, but practical results useful for wide energy applications are still eluding the photochemical approach.

Practical solutions of the intermittence problem may be obtained by combining different energy sources, and large-scale electrical networks may readily absorb intermittent sources output. Similar principles may be applied on a smaller scale, such as in mechanical storage by pumping water into pump-storage reservoirs for later production of hydropower or by compressing air for later use as mechanical energy. Another way would be to store hydrogen gas, produced by electrolysis, for use in place of other fuels in combustion engines [3].

Any improvement in the present methods of storing solar energy will have wide applications and will open the way to extensive and more economic utilization of solar energy [68].

Future solar energy collection, storage and conversion possibilities can be sharply silhouetted against present fuel depletion. Though it is not yet known what catalyst to use or the details of the process, a long range research program should make it possible to combine carbon dioxide, water, and the sun's energy to form carbohydrates and/or hydrocarbons for liquid fuels at low cost. Then it will be possible to solve the problem of liquid and gaseous fuels in the future. Solutions to long-term energy problems will come only through research, largely of fundamental character, in areas that may initially appear for removed from their eventual application (10). However it is now known that solar generation of electricity holds the promise of an abundant source of power, and that solar energy systems can be designed with a minimal effect on the local heat balance.

It is convenient to make a distinction between natural and technological processes for solar energy utilization (24), as done in the following two sections.

## A. Natural Processes

A natural storage of solar energy originates in the atmosphere, giving rise to wind on the earth's surface, resulting in the creation of temperature differences in the ocean; and through photosynthesis of plants [24].

### 1. Wind

Solar energy sustains the winds, and cn an annual basis the winds are repeatable and predictable. The kinetic energy of the moving air can be extracted by an air turbine or similar device properly located. A wind energy conversion system suitable for large scale power production would incorporate a storage substation for base and peak capacity to span the gap between the variable wind and electricity needed. This huge freewheeling wind energy is really energy stored in fluid momentum, and is a continuing power source only to the extent of its natural rate of regeneration. The regeneration rate is indicated from a summation method of surface friction in latitude belts $5^{o}$ wide. This method indicates that the total energy dissipation rate over land would be about $167,500 \times 10^6$ kw for the northern hemisphere in winter, and roughly $24,000 \times 10^6$ kw at the same time on land in the southern hemisphere. These figures indicate that the sun is generating wind energy, in excess of losses by friction over land, of about $0.19 \times 10^{12}$ kw, or at least $1700 \times 10^{12}$ kwhr/year. Only a small part of this power is within reach of ground structures, but

it has the advantage of not involving an intermediate heat phase. The wind power, as an assumption, through 175-ft propeller turbines spaced 16 to the square mile over the entire land area of the world and operating an average of 2000 hr/year, would yield about 120 x $10^{12}$ kwhr/year [1].

Summing up the natural energy incident annually on land areas, it can be estimated that the wind friction is only 1% of the solar energy received on the ground, and only a very small fraction of this power can be developed for large-scale practical use [11].

## 2. Ocean

Between the Tropics of Cancer and Capricorn, where the intensity of incoming solar energy reaches its peak, 90% of the earth's surface is water. This surface layer is in thermal equilibrium with a temperature that never drops below 27.8° C. To the far north and south, the summer melt-down slides to the depths of the oceans and slowly moves toward the equator, forming the cold streams of the ocean. Both heat reservoir and heat sink are replenished annually by solar energy. Therefore, it is possible to modify a conventional energy conversion system to convert some of the energy contained within the warmer water into electricity. Naturally, the conversion efficiency will be very low - about 2%, and the cost of a facility is estimated to be within a factor of 2 of a large conventional power plant. For example, a collection system of units moored one mile apart over the area of the Gulf Stream are thought capable of producing annually about ten time the present U.S. electrical energy output [24].

Generating electricity with a vapor cycle operating between the warm surface and cold depths was demonstrated in 1929 by George Claude of France. He and his colleagues recognized the ocean as the cheapest form of solar collector. Temperature differences between surface and deep waters of 20° C were observed. Although such temperatures are adequate to operate special turbines built for the purpose, the amount of energy consumed by the auxiliaries in very large [44]. A technical and economical study for a 400,000 kilowatt power station based on this concept is presently under consideration [24]; it now seems clear that heat engines operating in the tropical oceans, capitalizing on the temperature differences between upper and lower levels, could provide a source of economical and pollution-free electricity.

French physicist Jacques D'Arsonval predicted in 1881 that man would someday mine the ocean for heat to power his civilization, rather than mine the earth for fossil fuels. Specifically, he suggested that a heat engine operate between the warm upper layer and the cold deep water of the tropical oceans. The power delivered from such a heat engine may be called "solar sea power", for the sun would rapidly restore to the upper layer the heat transferred to the cold deep water.

Because solar sea power is essentially pollution-free, and is renewable, it has special relevance today. If D'Arsonval's prediction is to become a reality, solar sea power must, however, pass the acid test of economic feasibility. The probability of economic feasibility is so high that advanced reactors, such as the liquid-metal fast-breeder reactors

(LMFBR) the Atomic Energy Commission is developing, will be economically obsolete before development is completed [95].

In contrast to solar sea power, where the ocean acts as the solar collector, power plants that require man-made solar collectors appear distinctly uneconomical.

The working medium of the sea power plant can be any fluid with a reasonably high vapor pressure at ambient temperature, and with good heat transfer characteristics; D'Arsonval suggested ammonia, among other fluids. More recently developed refrigerating fluids, such as a freon, might be preferable. The heat engine of a solar sea power plant would be similar in principle to standard heat engines.

The sketch of Fig. 4 gives an impression of how such a plant might appear.

The schematic diagram (see Fig. 5) shows the essential features of a solar sea plant, operating with ammonia as working fluid merely for illustrative purpose.

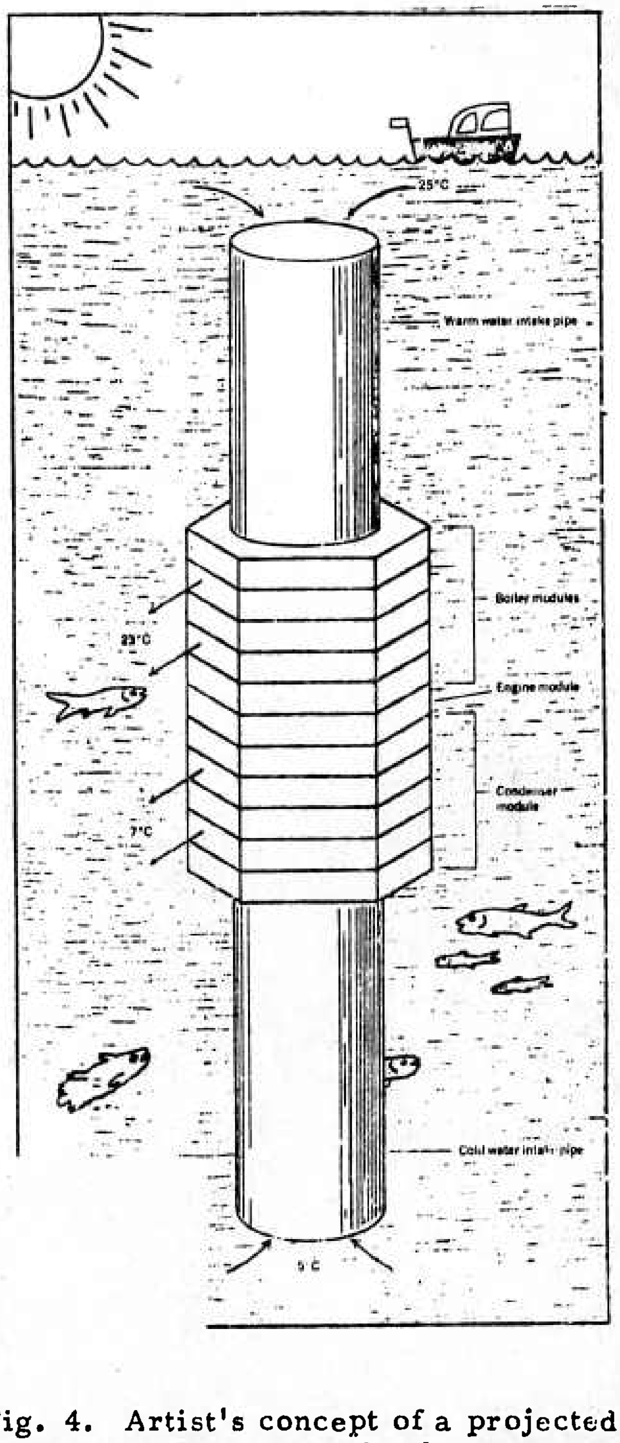


Fig. 4. Artist's concept of a projected solar sea power plant, operating between ocean levels at 25° and 5° C. The entire plant is neutrally buoyant at a depth of about 200 feet [45].

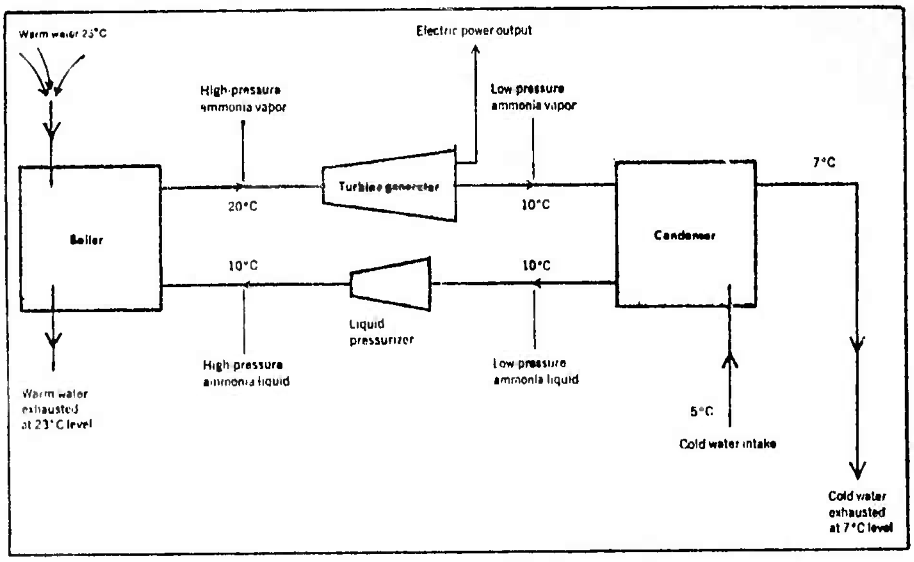


Fig. 5. Schematic diagram of a solar sea plant operating with ammonia as working fluid [45].

A reasonably high vapor pressure is necessary to avoid unreasonably large turbines. The economic failure of Georges Claude's attempt to develop solar sea power is probably due to his using the very low vapor pressure of sea water itself to drive his turbine.

The quantity of warm water that must pass through the boiler is, of course, enormous, but so also is the quantity of water that passes through a modern hydroelectric plant. In order to acquire a physical feeling for this quantity of water, let us calculate the work developed by the heat given up by one gram of warm sea water as it passes through the

boiler. According to the example, this heat is 2 calories, Carnot efficiency is 0.033, and ideal work is $2.8 \times 10^6$ ergs. This is just the ideal energy that a gram of water delivers to a hydroelectric power plant with a head of 93 feet. The quantity of warm water that passes through the boiler is thus comparable, on the basis of power output, to the water passing through a typical hydroelectric plant.

The thermal efficiency of the system is less than one-tenth that of a conventional modern fossil fuel plant, hence for the same power output the heat exchanger within the boiler must transfer more than ten times as much heat, implying that the heat exchangers must cost at least ten times more in our system than in a conventional fossil fueled plant. The fallacy to this argument is that the boiler tubes in a conventional power plant operate under the doubly adverse conditions of high internal pressure and high temperature. The high pressure requires thick walls, the high temperature requires still thicker walls or more expensive material. In contrast, a sea solar plant boiler would operate at only a very low pressure difference, and at ambient temperature.

The entire solar sea plant will be neutrally buoyant, submerged at such a depth that the vapor pressure of the working fluid will be largely compensated by the sea water's hydrostatic pressure. Thus, corresponding to a vapor pressure for ammonia of 105 $lb/in^2$ at $15^\circ$ C, the

appropriate submergence depth would be approximately 200 feet [45].

The various components may be arranged in a variety of ways. Scientists have suggested different arrangements to minimize the pressure difference (external and internal) to the boiler and condenser. There is a proposal, to minimize manufacturing cost, that the boiler, condenser and engine modules be all of the same standard size, i.e., 8 x 8 x 40 feet for convenient transportation.

The tropical oceans provide an especially favorable site for solar sea power, both because of their constant warm upper surface layer and because of the relatively shallow depth of the cold water. A typical temperature profile in the tropical ocean is shown in Fig. 6.

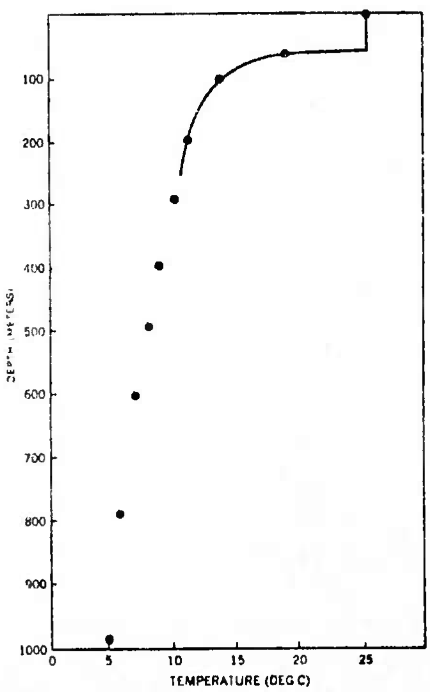


Fig. 6. Typical temperature profile in the tropical ocean. The black dots are readings at 8°22'N., 27°27'W. [45].

Solar sea power plants have not attracted the attention of physicists probably because their operation does not require sophisticated physics -- only sophisticated plumbing. But this very simplicity renders them amenable to cost estimation. The estimated cost (1965) of \$165/kw for a solar sea power was comparable to the then average cost of a conventional fossil fuel plant. Obviously, such economics did not encourage development of solar sea power at that time.

However, the power economics in the 1980's will be reconsidered through various factors, since the economics of energy is in a state of rapid change. Many independent factors are contributing to this change, such as the public desire for pollution-free air and water, the inability of the petroleum industry to satisfy the increasing demand for oil products, the reluctance to be energy-dependent upon the Middle Eastern nations, and the great distance of the largest coal reserves from large population centers. Although predictions are risky in such a stage of rapid change, most scientists and engineers believe that fossil fuels will ultimately be replaced by nuclear energy generated in large off-shore power plants. This suggests another variant of solar sea power, which is next described.

During recent years many scientists have recognized that our standard system of linking power stations to the ultimate consumer is especially uneconomical for large nuclear power centers. First, the demand for power is not constant in time, with a load factor at less than 50%.

Since almost 100% of the cost of nuclear power is in the initial cost of the plant, a 50% load factor doubles the cost of power. Second, the cost of transmitting and distributing electrical power is as great as the cost of generation, and will be several times greater if the public persist in demanding underground distribution. These two difficulties are simultaneously removed if the electric power is used to electrolyze sea water at the plant site, and the resulting hydrogen and oxygen gas is then fed into a pipeline network. Low-cost gas storage is already in common use, and pipeline transmission and distribution of energy costs only a small fraction of electrical transmission of energy. Such a system in which offshore-generated electric power is used to electrolyze sea water, and the resulting hydrogen and oxygen gas is then piped inland to fuel the economy, is now known as the "hydrogen economy".

Several studies have given a detailed analysis of the anticipated low cost of a hydrogen economy relative to that of an all-electric economy. A diagram (see Fig. 7) of such an economy based on solar sea power illustrates diverse applications to various branches of industry.

Of particular importance is the suggestion of using hydrogen gas as a vehicular fuel. Studies have shown that only minor modifications need to be made to a standard internal combustion engine to burn hydrogen.

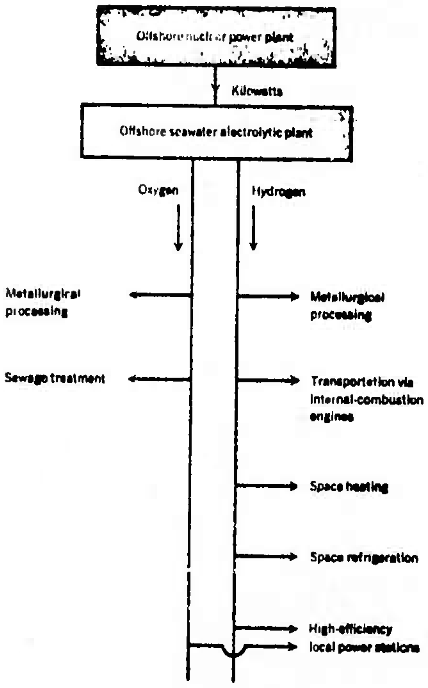


Fig. 7. The "hydrogen economy" and its application [45].

Not only are carbon monoxide and unburnt hydrocarbon absent in the emissions, but nitric oxide emission is much lower than when gasoline is the fuel. Hydrogen was actually used as a vehicular fuel in Germany during the late 1930's [45].

In a hydrogen economy the offshore nuclear plants would have to compete with solar sea power plants. Such tropically based plants could electrolyze water at depth, thereby producing hydrogen and oxygen at high pressure. These gases would be fed into submerged tankers, which would then be towed underwater to the appropriate coastal areas.

Coastal electric power plants fueled by high pressure hydrogen and high pressure oxygen from solar sea power plants will have fantastic properties. Conventional fossil fuel plants have either steam turbines or gas turbines; the steam cycle has the advantage that pressurization is performed upon a liquid; thus a large pressure ratio, greater than 400, and hence a high efficiency, can be obtained with a negligible irreversible loss. The disadvantage of a steam turbine is that it must be fed by a boiler, which costs as much as all the other power plant components combined. The advantage of a gas cycle is that combustion takes place within the working medium itself, so a boiler is not required. The cost of a gas turbine plant is therefore low. The usual disadvantage of a gas cycle is that pressurization must be performed upon a gas, and because of the inherent irreversible processes in a continuous flow gas compressor, the compression ratio is low, less than 20, hence the efficiency is low. However, a coastal electric power plant fueled by high pressure hydrogen and oxygen gas from the off-shore converter will have the combined advantages of the steam and gas turbine plants, with neither of their disadvantages. No boiler is required, because combustion is internal to the heat engine, and hence the cost will be low. No gas compressor is required, because the gas is formed at high pressure deep in the tropical ocean and hence the efficiency will have the high value associated with a high pressure ratio. Hence the efficiency of a hydrogen-oxygen plant will be even higher than that of a steam plant, because the absence of a boiler allows higher temperatures, and the cost of a hydrogen-oxygen plant will be even less than

that of a gas turbine plant, because the plant will not have boiler or gas compressor.

A hydrogen-oxygen plant emits only water and heat. If the exhaust is directly into the air, it will be similar to that coming from a cooling tower of a conventional power plant. The heat could also be rejected into the adjoining coastal water. In winter the exhaust could feed directly into a community steam heating system, or via heat exchangers into a community hot water heating system, eliminating the necessity of burning fuel for space heating.

It can be shown that tropical oceans could supply the whole world in the year 2000 with energy at a per capita rate of consumption equal to the U.S. per capita rate in 1970, and suffer only a $1^{\circ}$ C drop in temperature.

We should now ask what the qualitative effects are of lowering the surface temperature of the ocean. The most direct is, of course, a lowering of the tropical atmospheric temperature. A more subtle effect is revealed when we realize that the lower tropical surface temperature has been caused primarily by a transfer of heat from the surface to the deep layers, rather than by a removal of heat from the ocean. The lowered loss of heat by evaporation and by radiation, the heat input remaining

constant, results in a net heat input from the sun. This net tropical heat input must be dissipated outside the tropics, presumably by increased convection currents [45].

A new sea solar power scheme for producing power on a large scale, practically and economically, utilizes the basic Rankine cycle similar to that in the simple steam power plant. There is however an important difference, i.e., instead of steam as a working fluid, this plant uses propane (other designers propose ammonia, freon, etc.) [90].

The proposed power plant would be on a floating platform located in the open sea, where warm water is available in ample quantities, and cold water is available at depths of 2000 feet or more. A cold water pipe is suspended from the floating platform deep enough to reach cold water. The cold water is pumped to the plant from this depth. For a typical plant of 100,000 kw capacity, the cold water pipe might be 35 to 40 ft in diameter.

The warm water is taken from the surface through screens around the periphery of the floating plant, and is pumped through boilers, where the propane is boiled at high pressure of approximately 131 $lb/in^2$. The heat taken from the water lowers its temperature from approximately $27.8^o$ to $26.1^o$ C, evaporating the liquid propane into high pressure vapor

at a temperature of approximately 23.3° C. The propane is then used to drive a turbogenerator set.

The propane vapor flows from the turbine exhaust to the condenser where it condenses into liquid at approximately 12.2° C. The heat of condensation flows into the cold water which is heated from 6.1 to 9.4° C.

The condensed liquid propane is returned to the boiler by a boiler feed pump and the cycle of boiling, expansion and condensing is repeated, using the same propane continuously circulated through the power cycle. This solar sea power plant cycle is illustrated in Fig. 8.

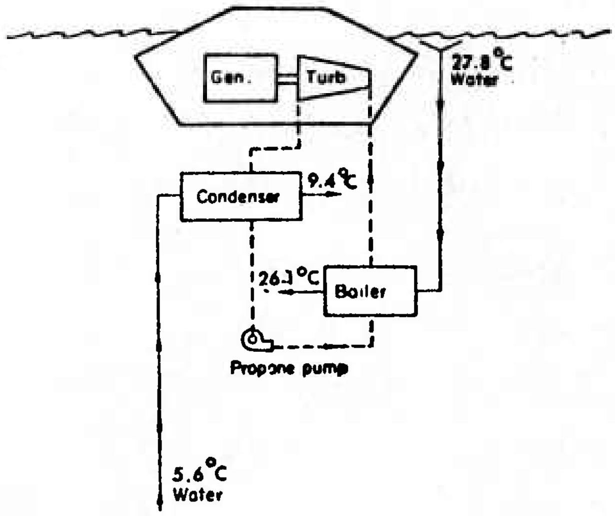


Fig. 8. Diagram of a sea power cycle [90].

It is possible in this way to produce power in any quantities at a lower price than that from any other major source of power. Here are a number of reasons why this new scheme can be practical and economically feasible:

- The floating plant permits sufficient movement to insure a continual supply of warm water without depletion;
- The floating plant permits short cold water lines, thereby reducing cost of pipe and pumping losses;
- The floating plant permits submergence of boilers and condensers thereby equalising the pressure of the propane inside to that of the water outside. This makes possible a low-cost heat exchange surface;
- The deeply submerged boilers and condensers and the suspended cold water pipe make the floating plant very stable and, with proper design, impervious to storms;
- The propane turbine is simpler, smaller and much lower in cost than the steam turbine. As an example, a 20,000 kw steam turbine would need to be approximately 32 ft in diameter with two stages running at 1000 rpm. The same capacity propane turbine could be 42 in. in diameter and run at 3600 rpm. It can be shown that the propane turbine cost would be less than 4 percent of the steam turbine cost for the same power output. The 3600 rpm generator would also cost much less than the 1000 rpm generator; and
- Propane is cheap, readily available, noncorrosive, and almost insoluble in water.

Besides producing power, the floating plant at sea can be used for the production of fresh water, a subject discussed in detail in Chapter IV.

A natural by-product of water desalting is cheap oxygen. The gases dissolved in natural sea water are composed of approximately 34 percent oxygen, whereas atmospheric air contains only 23 percent oxygen. Separation of oxygen from air is basically a refrigeration process, requiring heat exchangers, refrigeration compressors, a heat sink, and power to run the compressors. With a higher percentage of oxygen in the ocean supply, less refrigeration and equipment is needed. The cold water also provides a heat sink at lower than usual ambient temperatures, reducing required power input as well as the cost of compressors and heat exchangers. The condensed propane from the power plant condensers can thus be used as the refrigerant to cool the air to the oxygen plant. The propane from the boilers can also be used to energize propane turbines to drive the refrigerant compressors. This eliminates the conversion to electric power for refrigeration. These combined factors could reduce the cost of oxygen to less than half of what it is today.

A typical plant of 100 Mw gross power capacity and 60,000,000 gallons per day fresh water capacity could also produce 115 tons of oxygen daily from the gases that must be removed from the water. This can be an extremely valuable by-product with many uses [90].

A side benefit of removing oxygen from the water occurs because oxygen is the primary cause of the corrosive action of sea water on metals, hence removing the oxygen before passing the water through the boilers should virtually eliminate corrosion. It should also eliminate fouling by marine organisms, because of most them require oxygen to live.

With cheap power, fresh water, cheap oxygen, and location on the ocean, we have the basic ingredients for many kinds of chemical or metallurgical plants. For example, fresh water and oxygen are important ingredients to make low cost steel manufacturing possible. It is also important to have a steel plant located where cheap transportation for iron ore, coke, and limestone is available. Many steel plants are already located close to the ocean to reduce transportation costs. It becomes apparent that the sea thermal plant could be an ideal base for a steel plant. The steel plant can be located on shore close to the sea thermal plant, which could provide cheap electric power, fresh water, and oxygen, while ocean transport could furnish ore, coke, and limestone.

A little more advanced but even more logical plan would have the blast furnace on the floating sea plant. The power for the blast furnaces could be provided directly by propane turbines. Fresh water and oxygen would be available on the floating plant and deep water docking would

be available. Waste heat from the blast furnaces could also be used to generate power by boiling propane, expanding it through turbines, and condensing it in condensers cooled by cold water from the depth. It may seem farfetched to build a floating steel plant, yet no more so than present plans to build a floating airport or a floating city.

Another example would be an aluminum reduction plant. Today the major costs in reduction of bauxite to aluminum are for electric power and transportation. Fortunately much aluminum ore is available in the tropics where sea thermal plants can easily be placed, and the bauxite could be reduced directly to aluminum locally, thereby saving on shipping and power costs. Jamaica, for example, provides vast amounts of bauxite. This must now be mined and much of it shipped to Canada, where cheap power is available to convert it to aluminum; yet Jamaica provides a perfect location for a sea thermal plant. On the northeast tip of Australia are also some of the world's largest deposits of bauxite. Conventional power is not readily available there, yet just off the northeastern coast is plenty of warm water where sea thermal plants could be built for aluminum reduction [90].

Possibly the most attractive potential use for a sea thermal plant is to convert the chemicals in sea water directly into commercial chemicals and fertilizers. This opens up all kinds of possibilities. Bromine and magnesium are already being produced commercially from

sea water; concentration of the sea water into brine while producing fresh water and power should make bromine and magnesium production considerably cheaper than it now is.

Research has already shown that chemical fertilizers can be produced in the form of magnesium ammonium phosphate directly from sea water. If the sea water is concentrated into a brine by the desalting process, then the fertilizer manufacturing process should be lower in cost.

Another process under development is one that produces potash using sea water, limestone and electric power as raw materials. Sea thermal power and brine concentrated by desalting can furnish the cheap ingredients necessary to make this development economical. Many tropical islands are built from coral, which is practically pure limestone. In these tropical islands all the ingredients would be present for potash fertilizer production; all that is needed is the sea thermal plant to provide the energy.

It should be pointed out that if chemicals from sea water are the important consideration, then it would probably be preferable to use a freezing process to desalt the water. This process merely uses electric or turbine power, and concentrates the brine by yielding 50 percent or more of fresh water. With 50 percent of the fresh water removed from the sea water, the concentration of chemicals in the sea water is doubled, so that chemicals are more readily available than they would be from the raw sea water. Again, a number of useful products could be commercially obtainable from this brine.

With economical production of common bulk chemicals made possible by solar sea power, it is also quite conceivable that we can produce more exotic ones, such as gold, from sea water. There are many needed chemicals in sea water well worth the effort to produce.

It has been proposed many times that fish production could be increased by pumping cold nutrient-rich waters from the ocean depths to the upper levels, where sunlight can promote photosynthesis. This involves not only getting the cold water to the surface, but also warming it sufficiently so that it will stay in the 75-meter top layer, where photosynthesis and food production can occur. Fortunately, the sea thermal plant brings the cold water to a level near the surface as a by-product. When fresh water production is combined with power production, the cold water is also warmed by condensation of the fresh water vapor. The temperature is then high enough so that this rich, naturally fertilized water will stay in the intermediate upper layers, where it can serve as food supply for plankton and the entire marine organic life structure [90].

### 3. Photosynthesis

The natural conversion of solar energy into plant materials by photosynthesis and the future conversion of the stored energy into more

concentrated forms such as natural gas, petroleum and coal, is the basis of the world's fossil fuel supply. The managed efficient production of plant tissue (e.g. trees, water plants, algae) carried out on suitable land or water areas could provide starting organic materiais. However, the plant materials produced by photosynthesis have a comparatively low heat content. The conversion of plant material into higher heat content fuels is essential for effective storage and efficient use as clean fuels. By the year 2000, the bioconversion of organic matter to methane could provide up to 10% of the U.S. gaseous fuel needs [24].

The plant life cycle is a living example of the conversion of solar energy into usable chemical energy. Photochemistry, of which the photosynthesis of plants is nature's prime example, is the ultimate hope of man in putting this wasted energy of the sun to practical use [21]. Photosynthesis is the photochemical storage of solar energy in living cell systems. However, the average efficiency in the storing of the solar energy by the plant cover over the land and the algae in the upper layers of the ocean is probably less than 1 percent [10].

Sunlight provides the energy that effects plant growth which is recoverable from nature's photosynthetic products. Based on this photosynthesis concept, considerable work has been achieved in the field of quantitative photochemistry. In the 20th century scientists have begun

to pin down the quantum efficiency of photochemistry and to solve the problem of how chorophyll changes light into chemical energy. But even after more than two hundred years of investigation, there is little known today of how the plant achieves this deceptively simple transformation of energy from light to chemical storage [21]. The energy of the sun appears to fit into the cycle by causing the molecules of water to split into hydrogen and oxygen molecules, a process known as photolysis [20].

In 1961, Dr. Frederick Sisler of the USGS demonstrated his biochemical fuel cell in which decomposing organic material from the ocean bottom produced electricity. While his testing biocells convert sea water to electricity, he also proposed using algae to convert sunlight into electric power. It has been estimated that eventually such a power plant, also called "bug battery", may produce electricity at a cost of only one mill per kilowatt-hour, making it competitive with nuclear and even conventional power plants. With a maximum efficiency, the bug battery is surely one of the most intriguing possibilities for utilizing solar energy [21].

The raw materials of the photochemical reaction known as photosynthesis are water and carbon dioxide. The plant draws the water out the soil with its roots, and carbon dioxide is drawn through the leaves from the air. The energy that makes these two compounds combine to form carbohydrates is obtained from the sun. The formula for the reaction is known:

$$6CO_2 + 6H_2O \longrightarrow C_6H_{12}O_6 + 6O_2$$

Chlorophyll, which does not appear in the above equation, is a needed catalyst in the reaction. It has been determined that the chloroplasts, the basis of the photosynthetic process, are a complex compound of hydrogen, oxygen, carbon, nitrogen and magnesium, with the formula $C_{55}H_{12}N_4O_5Mg$.

The rate of photosynthesis increases in direct proportion to the intensity of sunlight, starting at about 1 percent of full mid-day summer sunlight, and reaching a maximum of about 35 percent of full sunlight. It takes place on cloudy days, and even under artificial light of suitable quality. However, the surrounding temperature is important, as most photosynthesis occurs within the range of 10-32° C. Increase in temperature causes in increase in the rate of photosynthesis up to an optimum, which for temperate-zone species varies between 16.7 and 30° C. Above this maximum the rate of photosynthesis actually falls off, as too much heat or cold can kill a plant [20].

Photosynthesis is only one example of the natural conversion and storage of solar energy. Fortunately, there are several simpler photochemical reactions, such as formation of free radicals, electron transfer, intramolecular rearrangement, photo-isomerization,

photoionization, photosensitized decomposition of unexited molecules, and photophysical processes such as photoconduction in solids, fluorescence, phosphorescence, etc. Not all these reactions appear feasible, since the basic requirements for a practical photochemical reaction are that it be endothermic and that it be reversible. However, many demonstrated photochemical reactions are not reversible, and many others are too quickly reversible. Therefore, a major problem is preventing these reversals until the stored energy is needed [21].

Despite the interesting possibilities of photochemical conversion, the inherently low power levels involved put them outside the scope of the present report and no further treatment will be given here.

## 4. Salt Flats and Salt Water Ponds

The most common method of solar energy utilization involving heat storage, besides water tanks or rock beds, is the use of fusion salts with melting points in the proper range. The salts store the heat energy by being melted, and when recrystallized they emit the stored energy [20]. A phase change, i.e., chemical change, using fusion salts is theoretically capable of storing more heat in a given volume than water tanks (ponds, reservoirs) or pebble beds. Sodium sulfate, $NaSO_4 \times 10H_2O$ and other hydrated crystals can be used very favorably. The solar heat is used to dehydrate the salt and, when the temperature falls below the transition temperature, an equivalent amount of heat is developed in the

rehydration of the salt. However, in the application of heat storage of this type more basic research on nucleation is needed. If the solution or the molten crystal supercools or the crystallization rate is too slow, the system may be impractical. In general, the heat conductance through a mass of crystals is slow. Therefore heat storage should be explored in systems that are stirred and in systems composed of small separate units with good heat conductance [9].

Salt flats are found almost in every continent, in desert regions usually near the Tropics of Cancer and Capricorn, or in landlocked areas. As the prevailing climate is that of a desert or steppe, the soil of these regions is sterile and the minerals usually are of little commercial value due to the high transportation costs. Another fact is that all these regions receive a very high amount of solar radiation, being one of the main reasons for their creation. Such areas, lacking other energy sources, represent a great potential for utilizing solar heat collectors for industrial purposes [25].

Solar ponds are large bodies of water, natural or man-made from 3 to 10 feet deep, with radiation absorbing layers near the bottom. The ponds absorb the solar radiation and are heated to reasonably high temperatures near the bottom. By "seeding" these ponds with salts, the hot layers stay near the bottom, and conventional heat engines can be operated between the hot bottom and cool upper layers. These ponds are

inexpensive and may cover large areas. However, more research is needed for full utilization, as these ponds show great promise [20].

Since the beginning of the 20th century, there have been suggestions for using salt water ponds of variable concentration as solar heat collectors. This proposition has been studied by various countries, but is still in an experimental stage. It is based on the maintenance of a salt concentration gradient to prevent natural convection. The suppression of convection within the solar pond permits about 50 percent of the solar heat to be collected for useful purposes.

A solar pond selected for the collection and utilization of solar heat must have a constant concentration gradient which creates a continuous, though weak salt diffusion from the bottom upwards. The salt that reaches the surface of the pond has to be eliminated by "wash water" which flows over the filled pond. However, this is not the only water required, since water lost through evaporation has to be replenished to keep the pond at its required depth of approximately 1.5 meter. An experimental research project in Israel reported that salt consumption for diffusion and washing equals 20,000 tons per $km^2$ annually [25].

French scientists suggest running the surface water into shallow black-bottomed ponds to be heated by the sun. A rise of only a few degrees was obtained even when heavy oil was used on the surface to reduce losses by evaporation [44].

In 1948, it was proposed that an effective solar collector could be made by avoiding convection in a stratified salt solution through creation of a density gradient in the pond. In certain saline lakes an increase in temperature with depth has been observed contrary to that observed in the oceans; stationary water is a good insulator and with a nonconvecting black-bottomed pond should act as an efficient solar trap.

The salt solutions used (mainly magnesium chloride) behave very much like pure water as far as optical absorption is concerned. However, if they are slightly dirty or have suspended matter, the transmissivity can be much lower.

The extraction of heat is one of the most interesting and difficult aspects of the solar pond, and it can be accomplished as follows [44].

o by an array of pipes on the bottom through which a heat exchange fluid is circulated;

o by drawing off a layer of liquid from the bottom of the pond into an external heat exchanger and then returning liquid to the pond.

However, there are several problems to be solved in overall engineering design of a solar pond for the production of electric power, such as:

o the type of surface condensers, to provide fresh water as a by-product to the power, as an alternative to the cheaper jet condensers;

o flash evaporation from the pond brines; and

o low-temperature turbines designed for variable temperatures.

In general, solar ponds may be used to produce low-temperature heat, i.e., below $100^{\circ}$ C for the chemical industry and other purposes at a price below that required by conventional fuel.

It was estimated in 1961 that a solar pond constructed on flat ground, with an available free source of concentrated brine (from a nearby sea), would cost about $250,000 for one square kilometer size, i.e., 25 cents per square meter, or two orders of magnitude lower than the cheapest present day solar collectors. Thus, the power produced would be very cheap and, used as a source of low temperature, the pond would pay for itself twice over in the first year* of operation [44].

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* Because of heat losses, the useful energy extracted is only about half that reaching the bottom of the operating temperature of 80-$90^{\circ}$ C. The collection efficiency is thus 15-20 percent, or the yield about $30 \times 10^{10}$ kcal/$km^2$ annually. This is equivalent to 36,000 tons of fuel burnt at 85 percent efficiency.

The solar pond thus holds out promise for being the cheapest known method of exploiting solar energy and is particularly suitable for large installations. A one square kilometer pond in a sunny climate should yield 30 x $10^6$ kw of power, equivalent to 6,000 kw installed and a 58% load factor, or alternatively about 30 x $10^{10}$ kcal of heat at temperatures around 80-90° C, equivalent to about 36,000 tons of conventional fuel burnt at 85% efficiency. However, three major problems remain to be solved for a solar pond to be practical and economical:

- the extraction of heat from the bottom without disturbing the density gradient;
- the suppression of upper zone mixing by wind waves, and
- the methods for keeping the pond clean [44].

## C. Technological Processes

Direct conversion of solar heat to electricity may be achieved by thermoelectric converters or thermocouples, and by thermionic or thermoelectronic converters.

Direct conversion of solar light to electricity can be achieved through two types of photoelectric converters: the photogalvanic (or photochemical) cell, and the photovoltaic cell, also known as a photoelectric cell or solar battery [3].

These devices have some advantages over the conventional steam power installations, the principal one being the absence of moving parts. They are also comparatively simple to operate, and it is expected that some of them may prove economical in the future for generating capacities ranging from several watts to one or more kilowatts; they could be used as a power supply for communication, small-capacity water pumps, lighting small houses, etc.

### 1. Thermoelectric and Thermionic Conversion

When speaking of thermal conversion, the term "new method of converting energy" is somewhat misleading, as the physical phenomena on which thermal conversion is based have been known for a

very long time [23]. The phenomenon of thermoelectricity was discovered in the early part of the nineteenth century; the practical utilization thereof, for purposes other than temperature sensing, is only now achieving feasibility for providing less limited power requirements.

In thermoelectric generators, an electric current is produced by heating one junction in a circuit or loop of two different metals or semiconductors and by keeping the other junction cool (such as by pumped water in the case of a water pumping supply). The efficiency depends greatly on the metals used. Another basic factor is the temperature achieved and endurable by the metals; the lack of practical applications of thermoelectricity over the past century has been in fact due to the low efficiency of known materials. The potential applications of thermoelectric power generation are numerous, as the spectrum of devices and systems built or planned to date testify [50].

The first solar thermogenerators, however, were made only at the end of 19th century, and the first tube-type photocells, in 1930. Thirty years ago the efficiency of the conversion of solar energy into electricity by means of photocells and thermocells was only a few tenths of one percent, but by 1961, it was better than 10 percent. Many technical papers on the theory of these devices and on the search for various semiconductors show that it is possible to raise the efficiency of solar electric generators much higher, and to improve other technical and economic characteristics [23].

In general, a solar thermoelectric generating system offers a static, high reliability, maintenance-free system that is independent of any transported supplies once installed. The maintenance-free aspect of this system makes possible its widespread application in nations where technically skilled personnel may be unavailable.

With respect to thermoelectric generator economics, the parameters of importance are the heat transfer aspects of the system, since these establish the amount of thermoelectric materials required for a desired voltage (which in turn defines the number of thermoelectric couples or basic units that must be connected in series), and the generator size. Based on various computations, the best estimate of 7 to 10 cents/kwh for the cost of electrical energy from a solar thermoelectric generator appears plausible in the size ranges of 500-1000 watts. With time, the efficiency ofthermoelectric materials should improve and mass production techniques will in all probability further reduce the per unit cost of electric energy. However, even at present cost levels, solar thermoelectric power generation appears attractive for many areas of the world [50].

Semiconductor materials for thermogenerators may be divided into low, medium, and high temperature types. Toward the end of the 1950's, thermoelectric semiconductor alloys with good characteristics were discovered, which made it possible to build experimental generators with efficiencies of up to 5-10%. By 1960 the theoretical efficiency of the

thermocouples had risen to 18% due to the improvement of intermetallic impurity of semiconductors. In the low temperature range the best materials for n and p half-cells remain solid solutions based on the compounds $Bi_2Te_3$, $Bi_2Se_3$, and $Sb_2Te_3$, developed in the 1950's in the Soviet Union. In the medium temperature range, lead selenide and lead telluride received the most attention; PbTe is widely used in the United States for thermoelectric generators. Scientists consider PbTe the most suitable material for generators, though it has several serious disadvantages: it is brittle, oxidizable, rather expensive, and gives a poor contact.

The first reports concerning solar thermoelectric generators appeared toward the end of the 19th century and early in the 20th. In 1954, the first solar thermoelectric generator was tested in the U.S. without a focusing collector. The thermocouple materials were ZnSb and an alloy of bismuth and antimony. This generator had an efficiency of 0.63% and a power of 0.156 watt.

In 1955, Soviet engineers at the Institute of Power Engineering im. G. M. Krzhizhanovskiy of the Academy of Sciences USSR designed a solar thermoelectric generator with ZnSb - constantan thermocouples and a focusing collector, having a system efficiency of 0.8% and a power of 19 watts. The efficiency of the thermocouples was about 3.35%. Since then, engineers have developed solar thermoelectric generators in which each thermocouple has its own concentrator (cellular structure), and in the USSR a generator of this type based on tellurium compounds has been tested

to deliver several tens of watts at an efficiency of about 4% [61]. In order to improve the utilization of solar energy, the cascading of thermoelectric and thermionic generators is also being intensively investigated. One proposal suggests the construction of a solar thermoelectric generator consisting of several parabolic sectors, each of which heats a separate unit. Soviet scientists have also experimented with the aforesaid generators, and in 1959 a solar thermoelectric generator with a focusing collector was tested at the Institute of Power Engineering at Tashkent. The generator area was 0.016 $m^2$, that of the collector 1.12 $m^2$. The generator comprised 108 cells in which the negative element was $Bi_2Te_3$, the positive element was $Bi_2Te_3$-$Sb_2Te_3$, and the contact alloy was BiNi-Ni. The device was cooled by water, and the temperature of the cold junction was $70^\circ$ C. This device was tested for 100 hours. To ensure a uniform heat flow a facetted type reflector was used. In addition, a 2-watt solar thermoelectric generator, based on PbTe and PbSbTe, has been built and tested at the Physicotechnical Institute of the Uzbek Academy of Sciences [61].

Several solar thermoelectric generators without focusing collectors have been tested in France and the Sahara, using one generator having two glass plate covers with a total area of 17 $m^2$. This unit delivered 5.5 watt/$m^2$ at a radiation intensity of 680 kcal/$m^2$, and about 7 watt/$m^2$ at 860 kcal/$m^2$. The thermoelectric material was bismuth telluride. The hot junctions were heated to $140^\circ$ C, and the temperature of the cold junction was 20-$25^\circ$ C above that of ambient air [23, 61, 67].

Soviet investigations on a photo-thermoelectrical solar energy converter indicate that the combination of photovoltaic cell and thermoelectric converter in the same installation will increase the energy output when compared with the output of the same devices working separately under the same conditions. The investigators conclude that the best materials for manufacture of such installations would be GaAs for the photovoltaic cells and BiTeSb for the low temperature thermoelectric elements. Tests have been run with the temperature difference between these two elements at about $12^{\circ}$ C [40].

Recently, Soviet scientists have conducted research on thermoelectric batteries with commutation through vacuum deposition. Nickel, iron, molybdenum, cobalt, copper with substrates of vanadium, titanium, and bismuth and its antimony alloys were used as the initial material for various testing. Additional study of the adhesion, contact resistance and technological efficiency in large scale production gave preference to cobalt. As a result of these tests, the possibility exists for the Soviets to begin production of thermoelectric batteries, utilizing the industrial BTKh 308/54 battery as the base. Thermoelectric batteries of the BTKh 308/54 type can be used as a component in thermoelectric converters for refrigeration, heat pumps, and low-temperature generators [81].

A solar thermal conversion system generally consists of a solar collector and thermal storage device delivering thermal energy to a steam turbine power plant. Through the use of high-temperature selective solar absorber coatings and concentration, temperatures suitable for standard steam turbogenerators can be achieved. Most current designs consists of five major elements: solar energy concentrator, receiver to absorb the concentrated energy, heat transformer (to thermal storage facility or to turbogenerator), thermal storage system, and turbogenerator. Estimates of efficiencies for converting solar energy into electricity range from 20 to 30%, and an area of approximately 10 square miles would be needed for a 1000 megawatt power plant [24].

The efficiency of the conversion of heat passing through a thermocell into electricity depends on the physical properties of the materials of which it is made and on the temperature of the hot and cold junctions. Conversion efficiency for a thermocell is determined with respect to the flow of radiant energy falling on the mirror of the solar thermoelectric generator. Consideration must also be given to the losses of energy due to the imperfect reflection of the rays from the mirror, incomplete absorption of the rays by the surface of the thermobattery, and the convection and radiation losses by the hot surfaces of the battery [23].

Among thermoelectric materials, compounds of lead (or bismuth) with selenium (or tellurium) have been most extensively investigated and widely used. Each thermoelectric material operates most efficiently and economically as an energy converter only within a certain temperature range. For wide temperature differences, it is necessary to design a multistage generator with each stage operating within its optimum temperature range. At very high temperatures, several technical problems must be considered. First, the material must have a sufficiently large energy gap to assure that it will remain extrinsic, i.e., that the hole or electron concentration will be determined by the impurity concentration. Second, diffusion in solids becomes quite rapid above 600° C; consequently extreme care must be taken to prevent diffusion of undesirable impurities (from soldered joints or electrical contacts, for example) into the thermoelectric material. Precaution must also be taken against oxidation of the material. The search for high temperature thermoelectric materials to overcome the above technical difficulties is still in progress [98].

Recent advances in semiconductor technology not only have improved the operating efficiency of thermoelectric generators but have reduced the cost of such units sufficiently so that soon they will be able to compete economically with the conventional rotating machine type of energy conversion units. Besides costs, thermoelectric generators have many distinct advantages over conventional units: they have no moving parts so that their maintenance cost is lower and they occupy less space and weigh

much less per kilowatt of output power. A lead telluride cell of laboratory scale (1 $cm^2$ cross section) maintained at a temperature difference of $600^{\circ}$ C is capable of delivering electric power of about 1 w. To increase output power, a great number of thermoelectric cells may be arranged together, and industrial units providing power in the kilowatt range are now feasible. The future practical possibilities of thermoelectric energy conversion depend on how successful the search for new materials operating efficiently at high temperatures will be [98].

Theoretically, if a thermoelectric generator has no internal losses due to thermal and electric conduction, its conversion efficiency approaches that of a Carnot engine. In a practical unit, the conversion efficiency is further limited by thermal and electric losses in the thermoelectric element.

Thermoelectric generators are essentially low-voltage, high-current devices, so it is important that the contact resistance at both junctions of a thermoelectric cell should be negligibly small compared to the resistance of the thermoelectric elements. At low temperatures, soldered contacts are commonly and satisfactorily employed. At high temperatures, pressure contacts are used to avoid diffusion of undesirable impurities into the thermoelectric element.

In the actual design of a thermoelectric energy conversion unit, other engineering considerations besides the choice of material arise, e.g. to determine the number of stages required, to minimize the heat loss other than conduction loss in the thermoelectric element, to minimize the ohmic loss of contacts, and to convert the low-voltage DC power into AC power efficiently. Thermoelectric generators of small output power have already been given enthusiastic consideration and will be in operation in the not too distant future [98].

By 1961, the fabrication of small generators was moving from development into manufacturing, with such purposes in mind as water pumping in less developed areas [3].

The thermionic converter is a static, high temperature heat engine that converts heat into low voltage direct current electricity. It consists of a hot surface to emit electrons by thermionic emission and a cool surface to collect the electrons (see Fig. 9). The two surfaces must be electrically insulated, and the space between the surface must be evacuated or filled with an easily ionized vapor.

An electronic generator must have a source of electric charge, must develop voltage to drive the charge, and should have a low internal impedance. The electric charge is generated in a thermionic

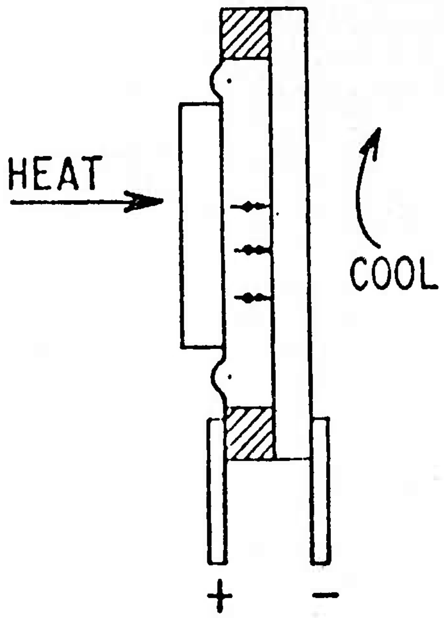


Fig. 9. Schematic diagram of a thermionic converter [49].

converter by thermionic emission from the hot electrode. At $1900^{\circ}$ K the overall efficiency is 9.5 percent, from which one may now estimate how large such a system must be to generate one horsepower (746 watts) of electricity. At 9.5 percent efficiency, this will require a total incident energy of 7850 watts. In desert areas and low latitudes, the incident radiation is 1.35 cal/cm$^2$/min or 0.095 watts/cm$^2$, thus requiring 82,600 cm$^2$ of mirror or a parabola 3.25 meters in diameter.

Thermionics has been the basis of many electronic devices and circuits used in communication, radar, radio, etc., for many years. The thermionic diode has been used for over 50 years; during this period

of time, several scientists indicated the possibility of using this diode for direct conversion of heat to electrical power, but rejected its practicality on the basis of negligible attainable efficiencies. Only since 1955 has a serious effort been undertaken by engineers to use a thermionic type of device to convert thermal energy directly into useful electrical power with reasonable values of thermal efficiency and of current density.

In 1960 the RCA Laboratories at Princeton, N. J., succeeded in reaching efficiencies of about 14 percent with a new three-electrode type of thermionic converter capable of producing electricity directly from conventional heat sources or from the heat produced by a nuclear reactor. In the earlier or vacuum type of thermionic converter, the spacing between the anode and cathode was kept small, to reduce the space charge effect. The first major improvement in this design consisted of introducing an ionized vapor, such as cesium, to neutralize the space charge and facilitate the flow of electrons. The cathode, however, had to perform the dual function of both ionizing the cesium gas and emitting electrons, and to do this effectively it had to operate at a temperature of not less than 1930° C.

RCA overcame this difficulty by adding a third electrode or element to ionize the cesium. Since this element does not have to emit electrons as well, it can be kept at a temperature considerably less than 1930° C, permitting the use of a cathode with higher emission characteristics.

Both anode and cathode can thus be operated at temperatures of about 1094° C. RCA reported efficiencies as high as 14 percent with this improved design; by 1963, subsequent tests had shown efficiencies as high as 15-17 percent with cathode temperatures of only 1500° C [20].

There are presently several types of thermionic energy converters under study that depend on various means of controlling the space charge between the emitter and collector surfaces. The future prospects of thermionic energy converters appear very promising with respect to attaining thermal efficiences of 20 to 30 percent, power outputs of 10 to 100 $w/cm^2$ of emissive surface, small size per unit output, and high reliability.

The application of such converters will be for specialized use (space and military devices and systems), for standby power sources, and in competition with currently available power devices of small size and of all types. Furthermore, thermionic energy converters may be readily combined with other types of power plants that require lower input temperatures, so that in effect the thermionic device becomes a primary stage for the other power plants. Examples of such combinations are: a thermionic converter with its highest input temperature of 2000° K, which rejects heat at 1000° K to a thermoelectric generator; the combination of

a plasma thermionic diode; and the combination of thermionic unit with another power producer as for a solar powered space device, in which the heat from the thermionic converter is rejected to a Stirling heat engine, and the latter rejects its heat to space [99].

Solar concentrators and thermionic converters could probably be developed to convert about 9.5 percent of incident solar energy to electricity. A system to obtain this efficiency would be extremely complicated to build and would be expensive. If solar converters having ceramic envelopes could be developed, they would be less efficient, but probably the system would be less expensive to produce.

By the 1960's, thermionic converters were being engineered for use in converting solar energy to electricity for space vehicles. To adapt this development for inexpensive electric power on the earth, the converters must be redesigned to make them resistant to oxidation by the atmosphere and to make them less expensive to build. Different engineering approaches are proposed, e.g. to build several converters inside a large vacuum enclosure, the outer surface of which does not operate at the converter cathode temperature, or to build individual converters with ceramic parts to withstand oxidation by air at the high temperatures [49].

Compared to thermoelectric converters, the economic prospects are thus more uncertain for thermionic converters. The initial cost of the converter alone may be on the order of $2,000 per kilowatt, but with further refinement and mass production, costs might be brought down significantly [3].

2. Photoelectric Conversion

Despite its cost, the silicon photovoltaic cell remains among the most efficient converters of solar light into electrical energy [59].

Early silicon cells of very small size and high resistance developed 2.5 percent efficiency, but it was not until shape, conductivity, and contacts were properly developed that it was possible to make cells of several square centimeters area which could deliver practical amounts of power. These cells were first called power photocells because they were intended to be used as power sources and not merely as sensitive circuit elements. Later, when batteries of a tenth of a watt and over were constructed, the term "solar battery" was applied to them, although the term has been loosely used to cover any device converting useful amounts of solar energy directly into electrical energy [14].

Practical silicon solar converter efficiency is now 10 to 15 percent. In principle, InP and GaAs converters with band gaps near the optimum should be of higher efficiency; actually, basic fabrication difficulties preclude this achievement. An efficiency of 50 percent might be obtained in a three-semiconductor "sandwich" assembly, with the widest gap semiconductor on top utilizing the highest energy photons, the medium gap the next lower energy, etc. Other schemes using converters with continuously varying band gaps have been proposed; they have not been realizable because of limitations in the technology and economics of compound semiconductors.

Silicon solar converters are widely employed in both terrestrial and space applications. Such converters are used in conjunction with storage batteries since, in both applications, there is insufficient light at times. For terrestrial use, the converters are oriented for maximum insolation at the winter solstice and an economic balance between the number of converters and storage batteries is made consistent with power requirements [60].

Various opinions prevail concerning the feasibility of such solar power stations, and it has been calculated that a 1000 kw station with an efficiency of 8% would require a battery of silicon cells with an area of 12 to 15 acres. Construction of such station is still a difficult task [59].

In considering the prospects of utilizing photovoltaic cells for power supply, apart from such measures as increasing the efficiency, using new material, improving techniques, etc., it is also necessary to increase the energy yield per unit of active surface area by intensifying the light flux reaching the cell. There are several reports on the use of focusing mirrors and lenses to intensify the light flux incident on photovoltaic cells, and on the construction of portable installations for converting solar to electrical energy. The problems connected with photocell technology have been worked out only for ordinary light intensities; as far as very intense light fluxes are concerned, these problems are still in the testing stages since studies began in 1965 [59].

Another very successful device for direct conversion of solar energy into electric power is the barrier-layer photovoltaic cell [10]. The barrier-layer cell was developed about 90 years ago, using selenium as the light-sensitive material. Modern selenium cells are widely used in present-day industry for such diverse purposes as photographic exposure meters, photoswitches and photoelectric eyes. They have an overall conversion efficiency of about 0.6 percent when operated in direct sunlight.

In 1954, the Bell Telephone Laboratories succeeded in improving the efficiency of photovoltaic cells to 6 percent through the use of a thin boron diffused layer on the surface of single crystal n-type silicon.

A great deal of development work has gone into such devices over the years, and by 1961 they were commercially available from a number of manufacturers at efficiencies of up to 14 percent for converting the solar radiation incident upon them directly into electric power. This conversion efficiency compares favorably with other types of modern power plants, such as the gasoline engine and the steam generator. It is therefore technically feasible to use solar batteries as power supplies at locations remote from commercial power lines [34].

The development of transistors and semiconducting electronic devices was instrumental for the development of a silicon photovoltaic cell with 6 percent conversion efficiency. Several improvements have since raised its efficiency to about 15 percent, and there were predictions that this could be raised above 20 percent. However, there are factors which tend to limit efficiency, such as:

- losses through the recombination process;
- partial dissipation of electric energy within the cell;
- losses due to the fact that not all radiation from the sun is in a wavelength region that will provide photons with a sufficient energy effective in the needed process, while some photons have too much energy and that excess is lost as heat; and
- loss of radiant energy through reflection from the silicon surface [10].

The main drawback of photoelectric converters is their high cost. Different ways proposed by various investigators to overcome this include the following:

o the use of polycrystal materials, which reduces the cost considerably but also reduces the efficiency;

o the use of "double-sided" photoelements and a common optical system with poor concentration of solar rays, which permits a twofold to fourfold increase in the energy output of a unit of the photoelement surface; and

o the use of high concentrations in artificial cooling of the photoelements and reducing their internal resistance, which would allow a considerable increase in the energy output per unit of the photoelement surface [23].

Silicon photocells used in the early 1960's in the Soviet Union had efficiencies of 10 to 12 percent [48]. Since they were rather expensive, it was deemed important to study ways of reducing their cost and to find methods of increasing the power per unit operating area of the photocell. One of the suggested ways of reducing the cost of photocells is by using polycrystalline silicon in place of single crystals as the initial material, since photocells of polycrystalline silicon available at that time were two to three times cheaper than those made from single crystals. Under normal solar illumination, these photocells yield 5 to 6 $w/cm^2$. Their parameters vary with temperature and illumination, just as do the

parameters of single crystal photocells. The degrading effect of intercrystalline junctions has been eliminated by depositing a network of current taps on the working surface of the photocell [48].

In Japan, efforts have been made to reduce the high cost of silicon cells and improve their efficiency. Recently, inexpensive ceramic semiconductors were investigated for solar power generation. The sintered CdS cell is expected to be promoted as a photosensing device as well as a power source in space, despite a lower conversion efficiency than that of the silicon cell (6 to 9 percent). A sintered plate cell is characterized by the fact that the distribution of p-n junctions differs from that of single crystal, and a heterojunction model between p-type copper sulfide and n-type CdS has been established. Solar battery power sources were promoted by the development of the solar silicon cell more than a decade ago in Japan. Examples of industrial application there include microwave relay stations, unmanned lighthouses, repeater stations, buoys, and remote rain gauges (in combination with an alkali storage battery). The use of silicon cells as pyranometers and pyrheliometers has also been tried [58, 101].

Soviet scientists have been conducting tests to determine electrical and energy performance of highly effective GaAs photocells (efficiency about 13%) in comparison with Si photocells. Efficiency of these

cells at 200$^{o}$ C is 6-7%, which allows effective use of GaAs photocells with light flux concentrators [28].

Silicon photovoltaic cells have been improved through basic scientific developments so that, as already mentioned, 12 to 14 percent conversion efficiencies are now obtained in production quantities of these devices. The major improvements have consisted in increasing the lifetime of bulk silicon, introducing gridding techniques for contacts, and reducing the thickness of the diffused layer.

Other developments for the purpose of reducing costs for photovoltaic conversion of solar energy include the investigation of thin film silicon cells, studies of other materials, and increasing the area of silicon solar cells [57].

Significant cost reductions will have to be made for this power to reach large scale application. Remarkable strides are being made in this direction. One of them is in the form of experiments with concentration of the solar radiation, by which it has been shown that output can be increased twentyfold; however, with intensive concentration of radiation the solar cell has to be cooled in order to avoid the damaging effect of heat on its efficiency.

In [65] Menetrey notes that solar power systems which collect and convert solar radiation into electrical power appear to offer distinct advantages for space applications, as they are made under the general specifications required for terrestrial use. There have been attempts at large area solar energy converters which consist of small silicon spheres, typically 3 mm in diameter, diffused and embedded in plastic. Successive plating, lapping, and plating operations have produced finished, large-area solar converters. Researchers have shown that approximately 95% of the incident radiation can be absorbed with this geometry.

Since a semiconductor material of a specified band gap is best suited to converting only a narrow portion of the solar spectrum, considerable effort has been expended toward the development of solar cells incorporating more than one photovoltaic material. These cells take two forms. The composite form uses two or more separate materials incorporated into one cell with the incident radiation being split up and directed to the material best suited for each part of the spectrum. The "graded gap" cell is fabricated from a single crystal integrally composed of more than one material. The materials being developed for the high energy gap cell are aluminum antimonide and cadmium selenide. If these can be brought to a state of perfection approaching that of silicon, the composite cell could yield efficiencies approaching 20 percent.

In the early 1960's an extensive development program was begun to produce materials suitable for stacked or layered composite cells. This device depends for its success upon a material transmitting all radiation whose energy is less than its band gap to the cell below it. By stacking cells one on top of the other in order of increasing band gap, a major portion of the incident spectrum may be efficiently utilized. Efficiencies might approach 30 percent using composite cells [65].

Graded gap cells of this type have been proposed in several different forms, and are made by vapor depositing one semiconductor onto another or by pulling a crystal from the melt whose constitution is changed during the pulling operation. The primary purpose of the varying gap is to utilize the best photovoltaic properties of more than one material in a single p-n junction cell. One approach consists of diffusing phosphorus into a GaAs wafer to a predetermined depth and then diffusing a dopant, usually cadmium, into a GaP-GaAs wafer. Maximum theoretical efficiency of such a cell would appear to be 20 to 30 percent. Among other materials being investigated are CdS, GaAs, and CdTe [65].

There are possibilities of a radical departure with thin cadmium sulfide films, which may come to place photoelectric cells in an entirely new category and perhaps eventually bring the cost below $1,000 perkilowatt, or within the range of economic feasibility for home use [3].

Currently, the best cadmium sulfide cells are about 7 percent efficient. At the present state of development, these cells offer no advantages over silicon to compensate for their lower efficiencies. Gallium arsenide cells have been fabricated with efficiencies of approximately 11 per cent at room temperature and offer the best probability of eventually competing with silicon cells [65, 97].

In summary the cost of making solar cells needs to be further reduced, as it almost certainly will be. As pointed out, purified silicon is expensive; since the raw material is plentiful, cost here means fabrication technology. Certainly there will be a reduction in cost of purification of silicon and fabrication of finished cells. Just as diffusion developments have made possible the making of comparatively large area surface junctions, so also a new process whereby a really large surface could be sensitized without the preparation of single crystals would be welcome. It would be helpful to understand the present process more fully to make it more reliable and cheaper. The perfect contact to silicon suitable for solar cells has not yet been made, and the methods of assembly into batteries are far from perfect for a practical battery of long life. Hence other semiconductors are being seriously studied to compete with or to replace silicon [14].

3. Systems

Solar energy, at the rate of about 1 horsepower per square yard, requires collection over large areas. The solar energy can be collected as heat with or without concentration for obtaining higher temperatures or converted into other forms of energy. Concentrating collectors need direct, parallel rays of sunlight during clear days and cannot utilize diffuse radiation, which in some areas amounts to 50% of the total [20].

In general, solar radiation received on the earth's surface is not hot enough for technical use and must be concentrated by focusing from a large area onto a small heating surface, or must be retained in a heat trap for longer preservation. The focusing type collectors provide the higher temperatures needed for operating engines, but require direct sunlight and a sun tracking mechanism. Focusing collectors have mirrors arranged usually in a parabolic form, to focus onto a small boiler or heater. Nonfocusing collectors do not provide high temperatures and intermediate results are obtained by a permanently fixed flat reflecting surface tilted at an optimum angle equal to the latitude on the earth's surface. These collectors usually have two or more layers of glass plates, which allow the sun's radiation to pass through but are opaque in the infrared and

form a heat trap which keeps the heat-absorbing receiver from cooling off too rapidly, either by radiation in the infrared or by wind currents and convection [9].

The most common flat plate collector consists of a metal (copper) plate which is painted black on the side facing the sun and thermally insulated on the edges and on the reverse side (glass wool). Above the absorbing plate, spaced an inch or so apart, are one or more glass or plastic surfaces to reduce upward heat losses. The collected energy is removed by circulating water or some other working fluid in tubes which are in thermal contact with the absorber plate, or by circulating air past the absorber.

Schematics of several flat plate collectors are demonstrated in Fig. 10.

Design (b) is the conventional type described above; (a) uses air instead of water for heat transfer; (c) uses the glass shingle collector where heat is absorbed on the blackened bottom third of tilted glass plates and transferred to the air drawn down through these "shingles", and in (d) solar energy is absorbed on black gauze.

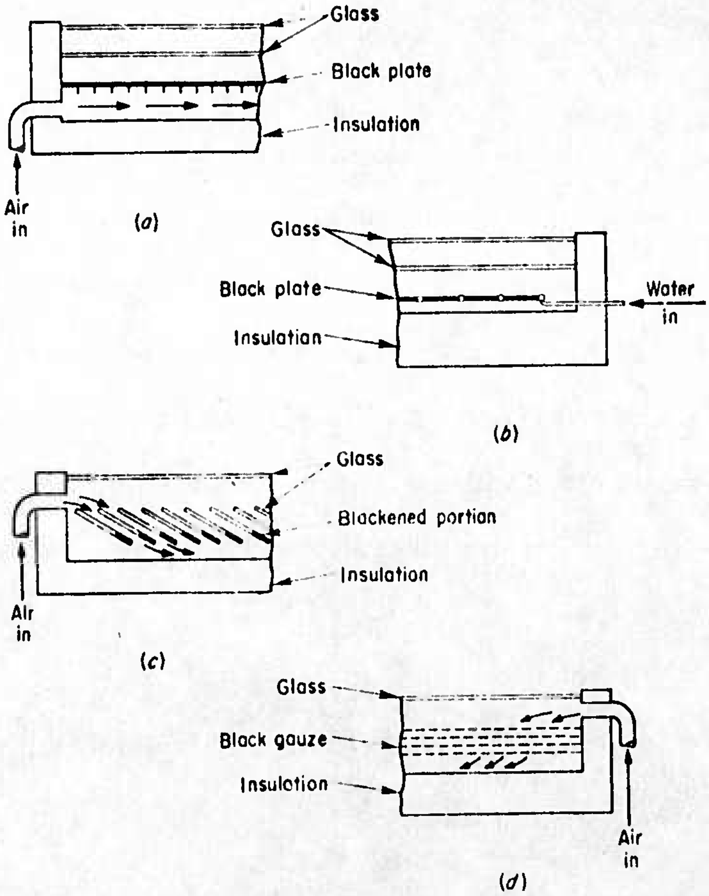


Fig. 10. Schematics of various flat plate collectors [22].

In general, the flat plate collector is a simple, rugged device which, without orientation mechanisms, can efficiently collect solar energy at moderate temperature levels. It has played an important role in the history of solar energy utilization and holds a position of great significance today. Flat plate collectors are economic media in connection

with space heating and air conditioning, and supplying hot water for domestic use. They have also been used with systems for the conversion of solar energy into mechanical and electrical energy. Flat plate collectors, unlike concentrating collectors, can take advantage of the diffuse component of scattered solar radiation as well as the direct component. The power absorbed per unit collector area for either one of these components is simply the product of the coefficient of absorption for solar radiation, the effective transmittance of the cover plates, and the solar incident radiation, falling on the tilted collector surface. The heat loss to the environment is made up of conduction loss from the back of the absorber plate through the insulating material (losses through the edges of a well-designed collector are negligible) and an upward radiation conduction-convection loss through the cover plates. The per unit rate of energy loss through the insulation is dependent upon the thermal conductivity and the thickness of the insulation as well as the difference between the arithmetic mean absorber temperature and the temperature of the back of the frame. In general the cover plates are, for practical purposes, opaque to the long-wavelength thermal radiation corresponding to the operating temperatures of the covers and the absorber surface [22].

The concentrator type of solar converter uses a collector comprising a concentrating mirror (or other optical device which focuses

the sun's rays to a small area) and an absorber which receives the concentrated radiation.

The types of devices which have been suggested for solar energy concentration span the gamut of optical technology, but only the following are potentially suitable for power systems application:

- o Paraboloid of revolution
- o Parabolic cylinder
- o Hemisphere
- o Circular cylinder
- o Conical mirror
- o Fresnel lens and mirrors
- o Dual mirror systems using either paraboloidal or hemispherical primary mirrors.

The relative merits of each type depend on the specific application. The concentrator types mentioned above are illustrated in Fig. 11. Each type forms a certain shape and size of focal image. The paraboloid of revolution, for example, forms a disk image at the focal point of the parabola. The spherical mirror, however, forms a circular rod image along the principal axis of the hemisphere.

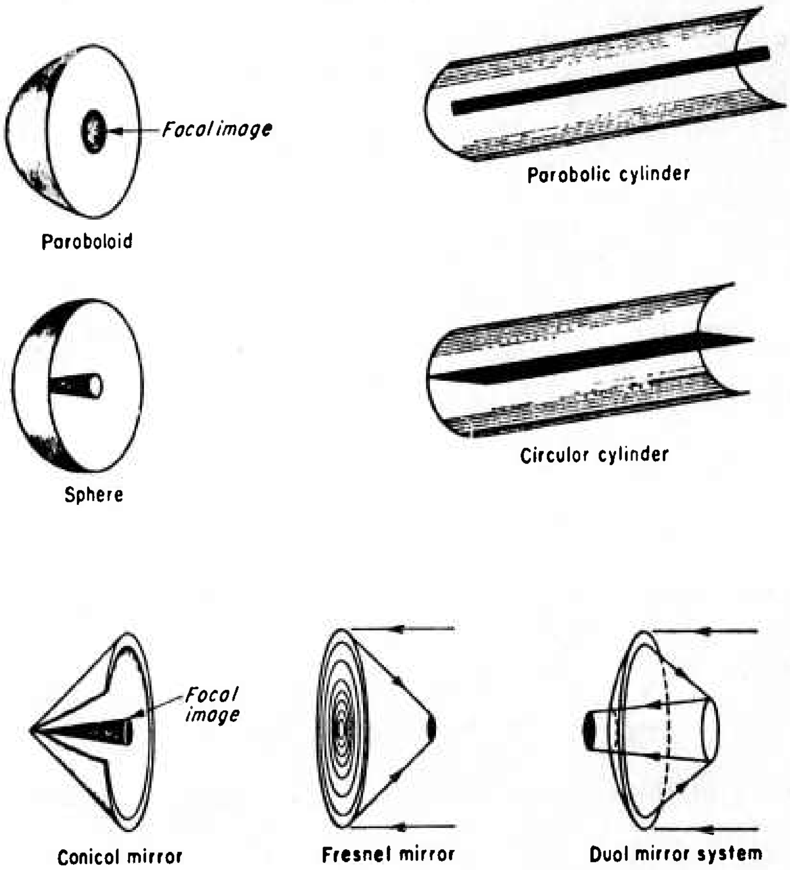


Fig. 11. Basic mirror shapes [65].

The need for high efficiency in solar power systems demands absorber temperatures as high as possible, consistent with materials technology. For higher absorber temperatures, the paraboloid of revolution is far more advantageous than other concentrator types, and development efforts to date have almost exclusively concentrated on the paraboloid configuration.

Devices for the conversion of solar energy to electricity can be broadly divided into those which use thermal processes and those which use quantum processes. The quantum process for recovering useful work is characterized by a cutoff wavelength, i.e., at longer wavelengths the photon energy is no longer sufficient to excite a chemical or physical change. The thermal process can be improved by using a selective absorbing surface such that the absorptivity and emissivity are high up to some cutoff wavelength and are low for all longer wavelengths beyond cutoff. In a quantum system all photons with energy greater than a cutoff energy can perform useful work. However, only a part of the energy of a photon with energy greater than cutoff is used in exciting the quantum change; the remainder of the energy in these high-energy photons in general is dissipated as heat (or light) [65].

Experiments have indicated that flat-plate solar collectors in conjunction with solar power plants convert only about 1 percent of the received sunlight to electricity. This rate can be increased by further design improvements to about 2 percent; when parabolic mirrors or reflectors are used, the efficiency goes up to 3 1/2 or even 5 percent. These are modest percentages, but the amount of electricity resulting from this much solar energy is by no means small [20].

With this brief background on general solar collecting techniques, let us review some experimental results that have been reported in the world literature.

In 1908, the Russian V. K. Tserasskiy developed and tested a solar thermoelectric battery whose hot surface was enclosed in a glass box. The material used for the thermocell was an alloy of zinc and antimony and silver-plated wire [13]. Tserasskiy also designed a solar oven in 1909.

A general view of a more recent Soviet solar energy converter is given in Fig. 12. To the flat frame of the concentrator, which is 4400 mm long and 3160 mm wide, there are attached 18 rows of

Fig. 12. Soviet solar energy converter [59].

plane mirror-facets, six to a row, for a total of 108. The rows are arranged nine on each side of the receiver which is supported above the center of the frame. Each facet is 0.5 m long, while the width, being a function of an angle of inclination, varies as follows (top line - number of row, bottom line - width of facet in mm):

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|
| 228 | 227 | 222 | 219 | 214 | 208 | 202 | 198 | 188 |

The facets are attached to the frame by the supports into which the mirrors themselves are rolled.

The concentrated solar energy is received by a specially designed silicon solar battery consisting of 3384 unit cells measuring 15 x 10 mm each (Fig. 13).

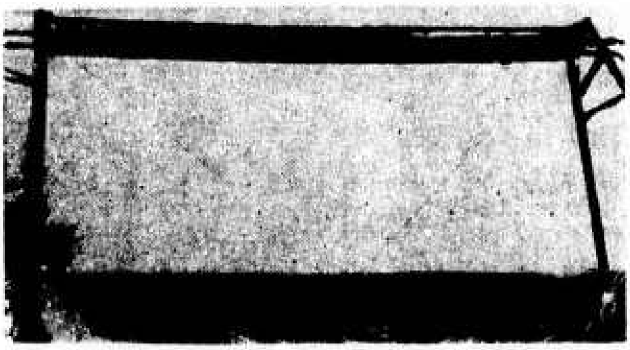

Fig. 13. Silicon solar battery, USSR [59].

The cells are fitted with auxiliary contacts to reduce the resistance to current flow. The battery is constructed of six separate sections connected together. The width (130 mm) and length (3000 mm) of the battery are equal to the dimensions of the focal strip.

The cells are fastened to a cooler with heat-conducting cement. The cooler is a hollow brass parallelepiped through which water circulates; the working surface of the battery is 0.4 $m^2$, and it is located 2690 mm above the center of the frame, a distance equal to the focal length of the concentrator. From tests on volt-ampere characteristics and power output, it was determined that the open-circuit voltage was 136 v and the short-circuit current 230 ma. The maximum power output was 20 w with a battery efficiency of 6.7%. The dependence of the overall efficiency of the installation on light flux is represented in Fig. 14.

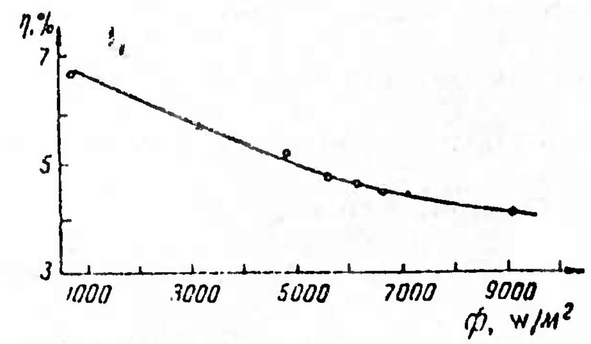


Fig. 14. Installation efficiency vs. light flux correlation [59].

Efficiency decreases as the light flux increases, since the output power is a nonlinear function of the incident flux. With about 250 sunny days or about 2000 working hours annually, the mean annual power output is about 300 kw/hr. About 400 liters of water per hour are needed to cool the cells and keep the temperature within the range of 60-70$^\circ$ C during the hottest day of the year. The tracking system consumes about 10% of the daily power output of the installation. During the test period, the installation charged a 10NKN-45 buffer battery. The power generated was used to operate two pumps that raised water from a depth of 6 meters [59].

Since 1960, the French have been experimenting with a new solar thermoelectric generator for industrial application of solar energy [67]. A generator having 17 m$^2$ in area is illustrated in Fig. 15.

Under transparent surfaces of glass or polyvinyl fluoride, which partition the space and reduce heat losses, the collector plates are heated by solar radiation causing heat flux to pass through semiconductor thermocouples of optimum conductance. The heat is then removed by a system of fins at the bottom of the generator. With collectors of uniform blackness throughout the visible and infrared spectrum, it is sufficient to use four transparent sheets, but with so-called selective collectors having a low infrared emissivity this number reduces to two transparent sheets. The sections of this generator differ in output; depending on the section, the

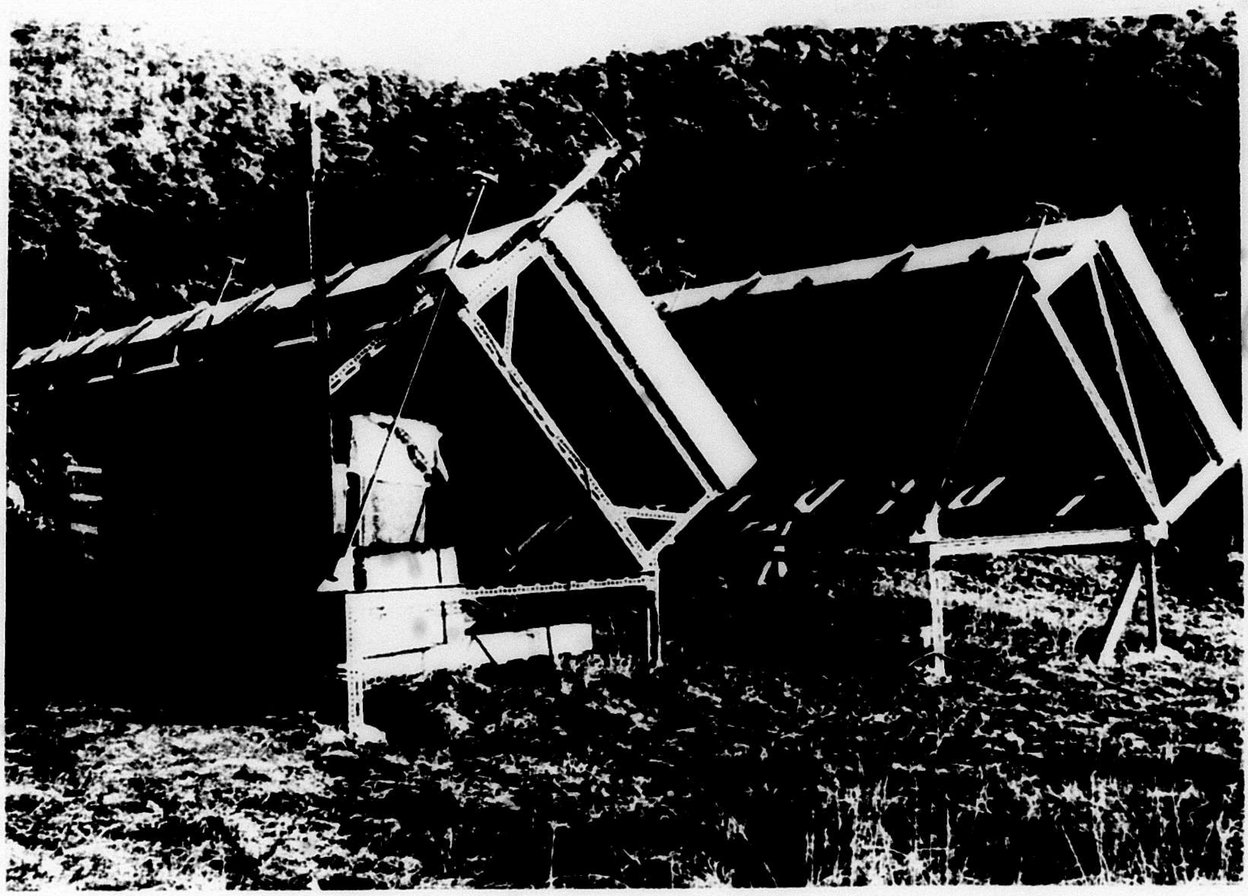

Fig. 15. Rear view of French 17 $m^2$ generator. In the foreground are the charging and measurement circuits, the anemometer and actinometer [67].

generator produces useful electric power of 3.7 - 5.5 watts/$m^2$ under a radiation of 850 watts/$m^2$, corresponding for the best section to 7 watts/$m^2$ and a radiation of 1 kw/$m^2$. In charging a battery of 16 alkaline cells, the generator operating above the radiation threshold of 450 watts/$m^2$ yielded a quantity of electric energy proportional to the radiation energy integrated

above the threshold, or a total yield of about 200 watt-hours per kwh/m$^2$ [67].

Among various methods of fabricating concentrators, considerable interest attaches to the method of "inflating" sheet material by means of a uniform applied load. The shape can be stabilized with epoxy resins. Concentrators of approximately paraboloid and parabolo-cylindrical shape can be produced by this method. In the USSR the All-Union Scientific Research Institute on Current Sources has conducted extensive research to evaluate the optical and energy characteristics of inflatable concentrators (Fig. 16 and 17).

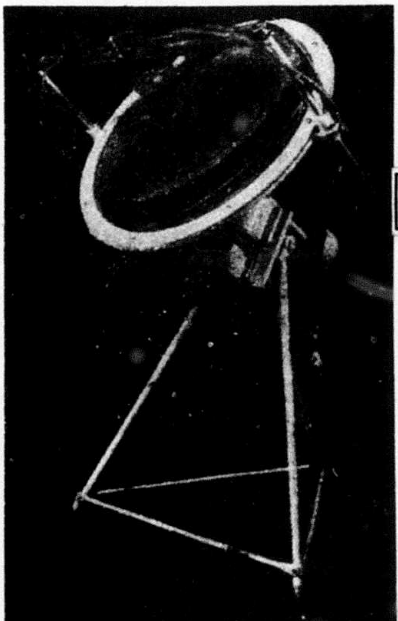



Fig. 16. Experimental inflatable concentrator, USSR [105].

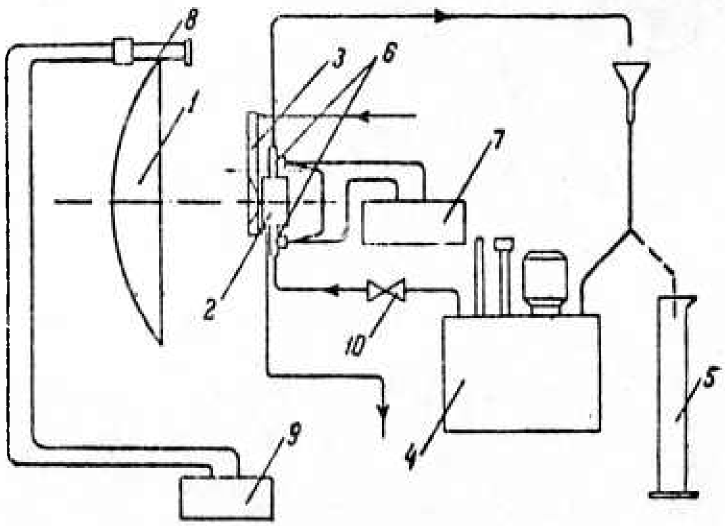


Fig. 17. Schematic of experimental inflatable concentrator [105].

1 - Concentrator; 2 - calorimeter; 3 - disk;
4 - temperature regulator; 5 - measuring vessel;
6 - thermocouple; 7 - potentiometer; 8 - actinometer;
9 - recording potentiometer; 10 - stopcock.

From these tests, Soviet scientists concluded that inflatable near-parabolic concentrators made of metallized film or sheet metal rigidized by polymer metals can be used in solar thermoelectric generators and solar heating devices for various purposes [105].

The same institute has designed and tested an experimental solar power plant to provide power for water pumps in the grazing areas of the southern USSR, as shown in Fig. 18 [106].

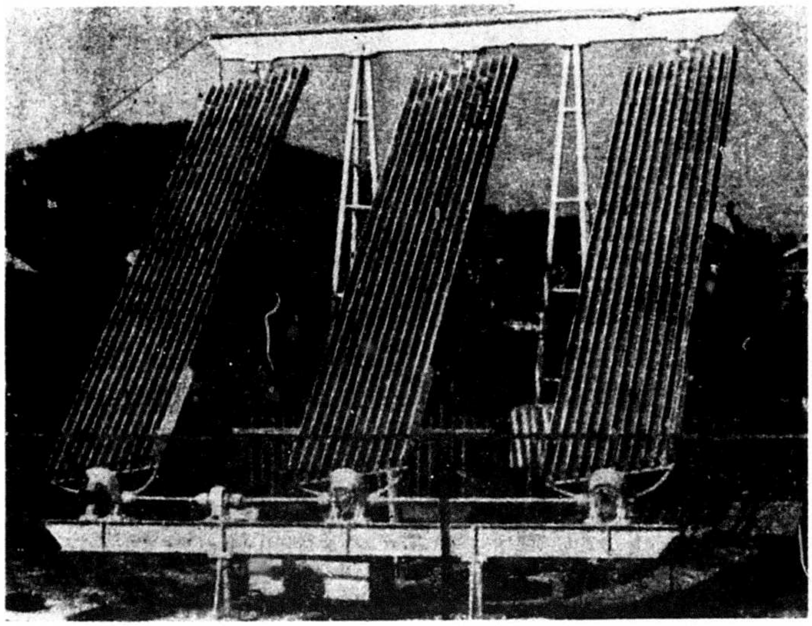

Fig. 18. General view of experimental Soviet solar power plant [106].

Solar batteries have been used mainly to power spacecraft and in some cases, at levels of several watts, for domestic purposes (transistor radios, etc.). Therefore, the planning and construction of the cited photoelectric solar power plant in 1964 with a capacity from several hundred watts to one kilowatt for the Soviet scientific community and national economy represented quite a technical innovation. This project was an experimental one to evaluate the performance and reliability of the design and operating characteristics of the plant and to determine the direction of further development in this field.

To avoid a special cooling system in this experimental device, a concentrating system was adopted that gave a concentration 2.5 times greater than natural solar radiation flux.

The solar battery, in the form of strips (Fig. 19) of width a,

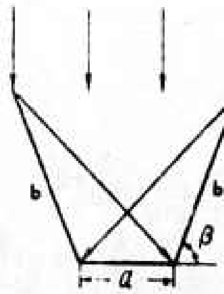


Fig. 19. Diagram of concentrating system.

(a- width of solar cell; b- inclined mirrors with $\beta$ angle of inclination) [106].

directly illuminated by the sun, receives additional illumination from inclined mirrors b situated at either side. In the developed design the solar battery, consisting of 30 mm wide strips, was combined with rows of concentrating mirrors to form 1 x 5 m panels. To track the sun, the panels rotate about a longitudinal axis parallel to the axis of the earth by an electric motor on a common shaft with reducing gear for each panel. The sun is tracked by a specially designed control system which also returns the device from the extreme western (evening) to the extreme eastern (morning) position and automatically switches on the pump motor when a given level of solar intensity is reached, and switches it off when the radiation intensity drops below a certain level. The distance between panels along the front was chosen so that they do not shade each other for an interval of 8-9 hours.

A storage battery is used as a starter and to supply power to the tracking system. The battery is charged when the solar radiation is either greater than the rated value, so that excess power is available, or below same set level so that the pump motor is not switched on. In general a storage battery is needed in any such system, since there are inevitably moments when the device must be aimed at the sun though the solar battery has not yet been illuminated and is not producing power. The consumption of energy for internal needs (powering the automatic switching and tracking systems) is small, not more than 5% of the power produced. The tracking system provides a sighting accuracy in the range from 10 to 60 min of arc.

This battery was designed so that at the optimal point of the load characteristic the voltage was about 40 v.

The device was tested near the town of Gelendzik, Krasnodarskiy Kray, RSFSR. One of the three panels was equipped with solar cells over only 2/5 of its area, so that the active area of the plant was 12 $m^2$ and the area of the solar battery 3.6 $m^2$. The plant was assembled virtually under field conditions without using any special hoisting or construction equipment. The structure proved to be sufficiently stable and despite its sail-like appearance it easily withstood high wind loads at wind speeds up to 24 m/sec.

The results obtained with this experimental solar power plant to drive a "Kama"-type electric water pump show that the use of such devices is technically promising. The design and automatic control system proved to be operationally reliable and simple to use [106].

The Power Engineering Institute im. G. M. Krzhizhanovskiy has designed and tested the type SV-1 solar water pump to be used in the grazing areas of Soviet Central Asia. This pump operates by a thermo-generator, a solar energy converter having a capacity of 20 v at 25 a. The parabolic mirror used has a 4.86 m diameter, focal length of 2.1 m, and an area of 18.65 $m^2$, and is illustrated in Figs. 20 and 21.

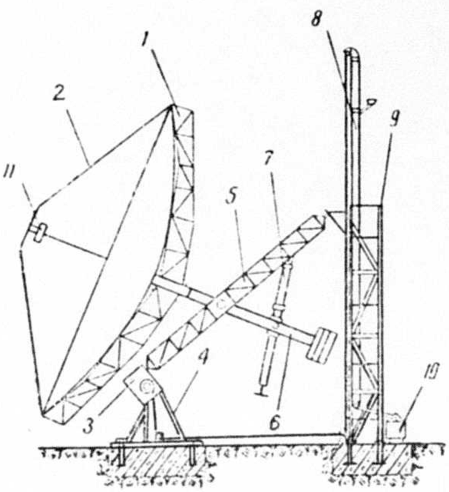

Fig. 20. Schematic of optical-mechanical parts of the converter [107].

1- Mirror; 2- bracket; 3- rotation reducer; 4- southern base; 5- axis of mirror's rotor; 6- central axis (coinciding with optical axis) with counterweight; 7- annual declination mechanism; 8- sand-driven regulatin; gear; 9- northern base; 10- sand container; 11- thermogenerator.

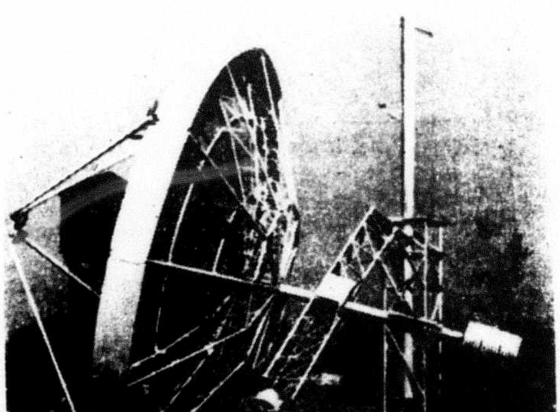

Fig. 21. General view of SV-1 solar water pump [107].

The SV-1 solar water pump is designed for prospective use in conjunction with a thermogenerator; however, it can be used in other projects, such as steam and hot water generation, water distillation, ice making, etc. [107].

The Institute of Solar Energy of the University of Algiers is conducting tests on a thermoelectric generator (Fig. 22 and 23), with a fixed position solar collector, direct exposure, low power, and designed

Fig. 22. Thermoelectric generator of the Institute of Solar Energy, University of Algiers [27].

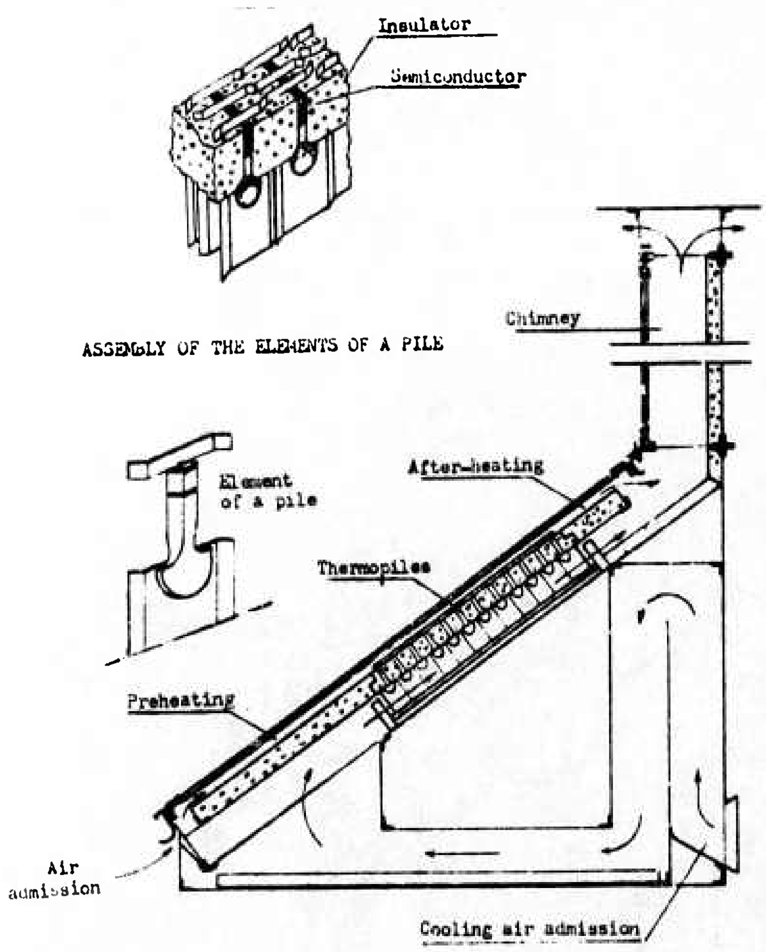


Fig. 23. Cross-section of thermoelectric generator [27].

for use in the Sahara as a power supply. It will be used for control systems, e.g. telemetering or remote control of meteorological stations, or for very small machines (air-conditioning fans, small water pumps, etc.).

The Physicotechnical Institute of the Uzbek Academy of Sciences has developed a vacuum film solar concentrator 2.7 m in diameter, to eliminate difficult and costly construction of a large concentrator made of mirrors.

This device (Fig. 24) consists of a reflecting film, a vacuum

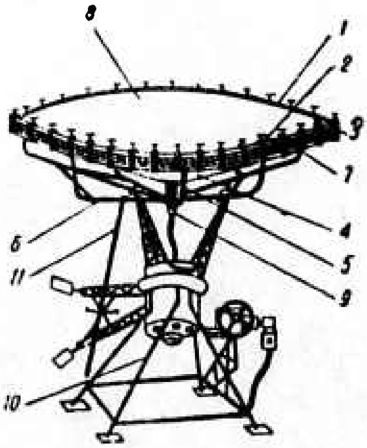


Fig. 24. Schematic of a vacuum film solar concentrator of 2.7 m diameter, USSR [41].

1- Outer rim; 2- clamps; 3- flange; 4- conical vacuum chamber; 5- bottom ring of frame; 6- mirror frame; 7- vacuum rubber ring seal; 8- reflecting sheet; 9- vacuum valve; 10- stand; 11- annual declination screw (manually operated).

chamber in the form of a truncated cone with hooped walls, and strute for vertical and azimuthal orientation toward the sun. The vacuum chamber is made of millimeter-thick galvanized iron covered with vacuum-deposited metallized polyethylene terephthalate. The polymer film, hermetically

attached to the open base of the conical vacuum chamber by the action of the pressure difference, affords a mirror surface with good reflectance for focusing the radiant flux. By varying the vacuum it is possible to get a concentrator with a desired focal length [41, 42].

Based on technical data obtained from their 2.7 m vacuum film solar concentrator, the same institute constructed and tested a vacuum film concentrator 5 m in diameter (Fig. 25). The reflecting area was

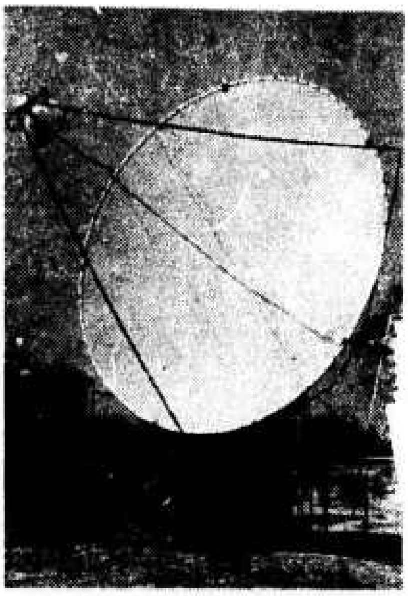

Fig. 25. General view of a vacuum film concentrator 5 m in diameter, USSR [42].

composed of 9 strips made from 56 cm wide film. A problem here is that under wind load the vacuum film reflecting area distorts, causing some displacement of the focal spot. The displacement amplitude of the focal spot depends on the directional force of wind and stability of the film. At

a wind velocity of 5 m/sec wander of the focal spot reached ±5 - 8 cm. Depending on wind load and stiffness, the stability of the vacuum film concentrator is reduced with increased diameter, which limits construction feasibility of large diameter vacuum film concentrator in a single piece [42].

Extending their research in polymers, Soviet scientists of the Physicotechnical Institute of the Uzbek Academy of Sciences in 1965 reported concentrators with thin epoxy resin mirrors which obtained favorable results under hot Central Asian summer conditions [55]. Owing to its low specific gravity, polyurethane foam is used for the lightweight transportable concentrators. Foamed polyurethane is obtained as a result of complex reactions by mixing the starting ingredients polyester, diisocyanate and water in the presence of appropriate catalysts and emulsifying agents. Polyurethane foam was used here to fabricate monolithic paraboloidal concentrators 280 and 410 mm in diameter and individual hexagonal facets with 55 mm long edges for subsequent assembly of facetted concentrators (Figs. 26 and 27).

The thermal characteristics of polyurethane foam concentrators are given in the following table:

| Concentrator | Temperature at focus, °C | | | | | |
|---|---|---|---|---|---|---|
| | Exposure, days | | | | | Radiation, kcal/m²·hr |
| | 0 | 15 | 30 | 45 | 60 | |
| Paraboloidal | 925 | 925 | 880 | 880 | 820 | 630 |
| Facetted | 250 | 230 | 170 | 115 | 115 | 700 |

Fig. 26. Paraboloidal polyurethane foam concentrator, USSR [55].

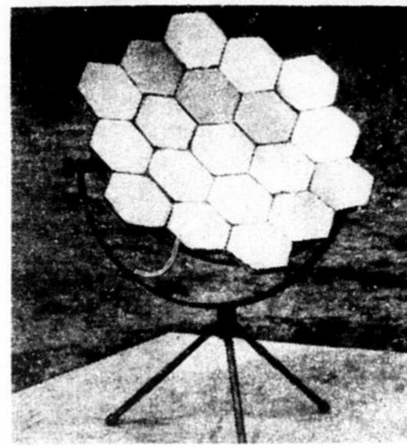

Fig. 27. Facetted polyurethane foam concentrator, made of individual hexagonal facets, USSR [55].

The strength of the polyurethane foam backing did not change as a result to exposure to the sun, but it turned slightly from light to dark yellow [55]. Fig. 28 shows another variant of this concentrator

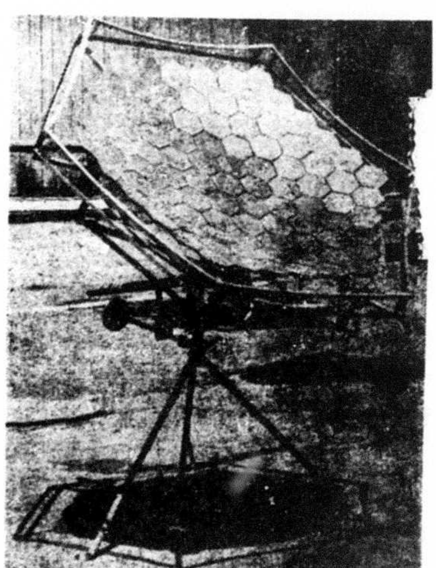

Fig. 28. Hexagonal honeycomb film-type solar concentrator, USSR [56].

built at the same Institute [56]. The concentrator consists of film-type reflector elements cemented to the rim of a frame with an epoxy adhesive and arranged to form the surface of a paraboloid of revolution.

The frame of this unit, a hexagon with sides 58 mm long, is of galvanized sheet metal. The reflectivity of the metallized film element is 0.86, and the weight of a single element is not more than 25 grams. A concentrator 1 m in diameter consists of 66 elements. Such concentrators make the construction of powerful solar converters more feasible and cost much less than comparable existing concentrators. In addition, they are simple to make in any size or configuration [56].

The same institute, has designed and tested a concentrator with an asbestos cement base (Fig. 29) [62].

The base was a mixture of 15% asbestos and 85% cement. The reflecting surface was formed by a metallized polyethylene terephthalate film on the asbestos cement base with epoxy resin glue, using a pressure differential process which prevented the film from being deformed during cementing. This concentrator is 92 cm in diameter and has a focal length of 47 cm.

Fig. 29. General view of concentrator on an asbestos cement base, USSR [62].

Test results indicate that the optical characteristics of this type converter are not inferior to those made of cast glass. The average integral reflectivity is 0.78. It is concluded that this type of concentrator will cut manufacturing costs, reduce the considerable weight of a spherical mirror, and allow fabrication of large reflecting surfaces with different configurations. [62].

Using the asbestos cement base technique described above, the institute has also designed and tested parabolic (Fig. 30) and parabolo-cylindrical film concentrators. Here the asbestos cement base is 5 m in

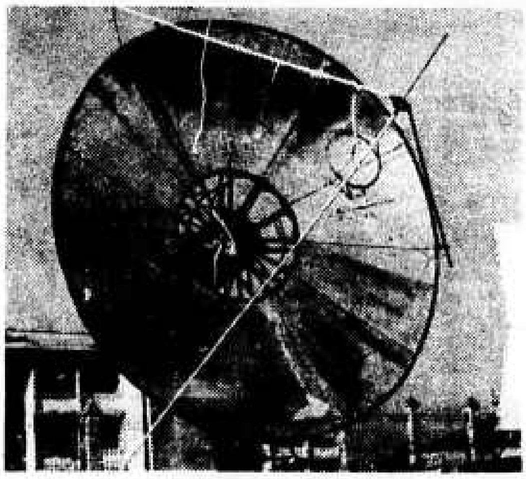

Fig. 30. Parabolic film concentrator on asbestos cement base, USSR [43].

diameter and is composed of 24 segments each having an area of 1.5 $m^2$ and a thickness of 8 millimeters. The type of film and cementing procedure are the same as on the 92 cm concentrator just described. Focal spot effective coefficient of the concentrator, measured by calorimeter, ranges between 0.6 and 0.65, with the average solar energy concentration ratio in the focal spot at 600, and maximum thermal capacity of 5-5.5 kw equivalent. Other parabolocylindrical film concentrators using the same technique have been designed with a reflecting area of 1.6 x 4.8 meters. The effective coefficient ranges between 0.7 and 0.75, with experimental maximum thermal capacity of about 1.2 kw equivalent and reflector focal length of 2.46 m. Focal spot solar energy concentration ratio is 20 [43].

A reflector with a large reflecting surface is necessary at the focal spot of a vacuum film concentrator for obtaining high power and a high temperature. The shape of the concave surface is appreciably affected by the weight of the film and wind loads, which result in a definite deterioration in optical and operating characteristics. Soviet designers have concluded, therefore, that large concentrators should be of the multielement type. The focal image of an ideal parabolic concentrator is sharp if the ratio of the focal length to the diameter of the parabolic reflector is sufficiently great. The same considerations apply to the elements of a multielement type concentrator [16].

The focal length of a vacuum concentrator depends on the difference between the chamber pressure and the ambient air pressure. An airtight chamber with a rigid 54 cm diameter rim was designed by Umarov et al. at the Uzbek Academy of Sciences to measure the position of the focal plane (Fig. 31 and 32).

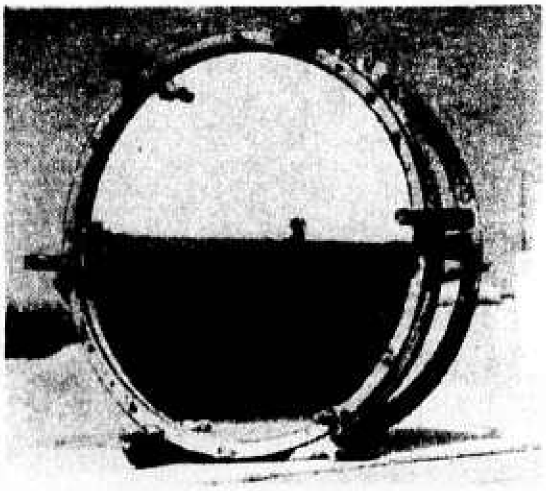

Fig. 31. General view of concentrator
(in the flat mirror configuration), USSR [16].

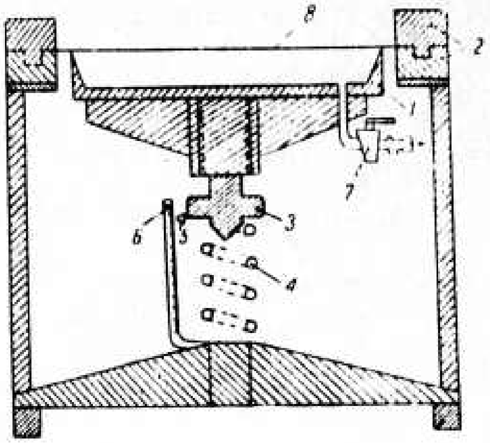


Fig. 32. Cross section of concentrator [16].

1- Metal disk; 2- rim; 3- drum; 4- spring;
5- indicator; 6- scale; 7- air evacuation tube;
8- metallized film.

The metal disk (1) has an optically precise rim (2) which rests against the stretched film (8). By rotating the drum (3), it is possible to make the film taut, thus giving it an optically flat mirror surface. The air is evacuated through tube (7), and the film acquires a concave shape due to the pressure difference. In fabricating a long focus vacuum concentrator, it is necessary to take into account the stretching force acting on the film. In addition, the metallized film should be secured to an optically precise rim and careful attention should be given to prestretching of the film.

The authors note that long-focus concentrators with focal length adjustment from 1.5 to 10 m can be made in this way. In this range the blackbody temperature in the focal spot can vary between 1200 and 300$^{\circ}$ C. At focal lengths greater than 10 m, wind loads adversely affect the optical characteristics of the concentrator [16].

In estimating the possibilities for large-scale output from these types of conversion systems, one should consider that a solar power plant of 100,000 kilowatt capacity requires a radiation surface (assuming chromium mirrors) of about three-tenths of a square mile, or roughly a million square yards, which is about 215 acres, equal to the area of Central Park in New York from the Plaza Hotel to the Metropolitan Museum of Art. This is admittedly a lot of space to fill with mirrors. It helps somewhat to substitute pure aluminum for the chromium, reducing the acreage needed to around 130, or something like 600,000 square yards. (An atomic power plant of the same capacity would take up about one acre).

In localities that have been under consideration, such as the valley of Ararat (USSR), the Sahara, and other unpopulated areas, the vast areas of ground surface needed for solar energy plants represent only a minor difficulty, but the installation and upkeep of thousands of mirrors is a little more costly, as well as the installation and upkeep of thousands of feet of piping. On the other hand, the "fuel" for solar power plants does not have

to be replaced from year to year as in an atomic power or conventional plant; in ten years an atomic power plant will have bought and consumed 90 tons of U-235 (and disposed of the radioactive wastes) while a theoretical solar power plant will have had to purchase no fuel whatever. Of course, the maintenance costs of the two are vastly different: replacement and polishing of mirrors, etc., vs. complete shutdown and decontamination of an atomic plant for two months or so every eighteen months, during which all equipment, machines, piping, gauges, and meters must be checked and replaced if defective or unsafe [20].

Where sufficiently large tracts are not available for solar power plants, solar energy can be converted to electrical energy by means of photoelectric cells and solar batteries. At the present time such applications are limited to small devices, like satellite transmitters and receivers, solar hearing aids, and solar clocks, but these devices work with a high degree of efficiency. Silicon cells, which serve as their basic working principle, are presently expensive but with common sand as one of the principal ingredients of silicates, perhaps in the not too distant future we will be using it to convert solar energy into mechanical power on a much larger scale [20].

Solar heat can in theory be readily converted to mechanical power for direct use as in water pumping and for further conversion to electricity by means of piston and turbine engines. This general field of technology has in fact been the subject of much of the historical attempts to devise heat engines from solar energy before the advent of photoconversion technology.

A hundred years ago little was known of the sciences of thermodynamics and heat transfer, but many inventors fascinated with the potentialities of solar power were known before that time. Early attempts at generating solar mechanical power continued up to World War I, after which there was a gap in research efforts owing to the ready availability of cheap stored fossil fuels. One of the earliest attempts was that of August Mouchat of France who between 1860 and 1880 built several steam-driven solar power plants which attracted the attention and support of the French government. Although a plant was constructed at Tours and tested by a commission of independent engineers, the French government finally condemned it as too expensive for commercial use [13].

Some of the most intensive early attempts to develop a solar mechanical power system were by John Ericsson (1803-1889) who is better known for his development of the Monitor of Civil War fame. His work covered a period of twenty-five years and is particularly noteworthy since he was probably the first to adapt the hot air engine to a solar power system. His solar power plant of 1883 (Fig. 33) incorporated a movable parabolic collector 18 feet in diameter with an Ericsson-cycle, hot air 6 inch tubular boiler which developed 4 horsepower [13].

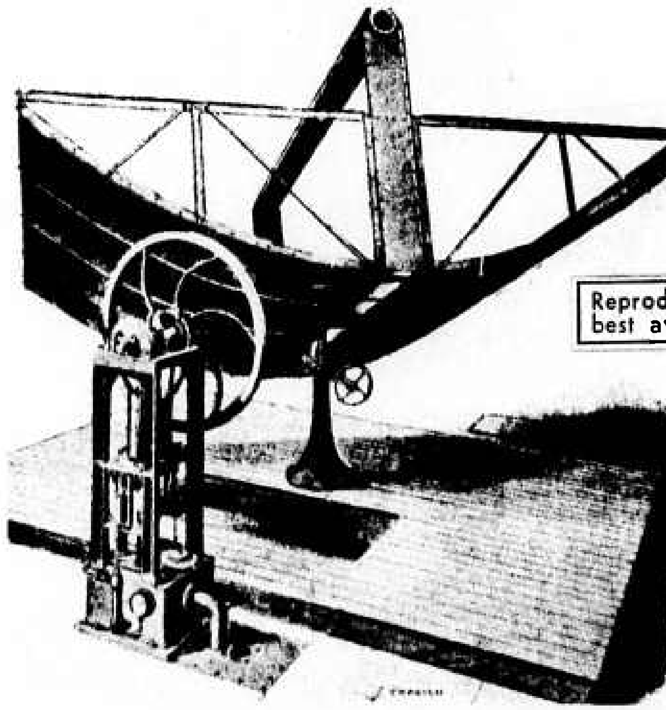



Fig. 33. Ericsson solar power plant, 1883 [13].

An ingenious solar motor was constructed by the German inventor Robert Schultz as early as 1881. Instead of water, Schultz used sulfur dioxide as the heat-transfer medium, the same gas which became so widely used in domestic refrigerators. Schultz's system conducted the $SO_2$ vapor produced by direct solar heating into a steam engine where heat was given up, which in turn was converted into mechanical power. He used a closed cycle, condensing the sulfur dioxide vapor and recirculating the liquid as in the modern gas refrigerator [20].

The first continuous-action solar motor was developed by the Austrian engineer Krenn in the late 1890's. Continuous-acting, of course, implies that it could run around the clock in any weather. Since Krenn's

claim has enormous implications for the future of solar energy, it will be worthwhile to examine his apparatus in some detail.

Krenn was highly original in his choice of a heat-transfer fluid, using mercury because of its high boiling point at 357° C. He used three parabolic mirrors in his device, each of which was equipped with a coil at its focal point, serving as an evaporator. A feed pump transported the mercury from the boiler into the uppermost of three tandem evaporators, and then into the other two evaporators below. The heat of solar radiation concentrated by the mirrors at the focal point vaporized the mercury in the evaporators, the mercury vapor being then carried to a mercury turbine by way of a flexible tube. On entering the turbine the mercury vapor had a temperature of about 389° C and a pressure of about 14 psi, or one atmosphere. At the exhaust end of the turbine, the vapor was exhausted into a water-cooled mercury condenser. At this stage the mercury vapor still has a high temperature, approximately 233° C at about one atmosphere, or enough to boil the water in the condenser tubes, and the steam produced in this manner was used to drive a steam turbine.

Thus Krenn's arrangement produced mechanical power from solar energy from two separate sources - a mercury turbine, operated by mercury vapor produced by solar heat, and a steam turbine, operated by steam produced from water by the residual heat of the mercury vapor after it had been used to drive the mercury turbine.

Krenn's extant drawings show that actually he used coal or coke to preheat the mercury liquid before it was vaporized in the "evaporators" placed at the solar foci of the three reflectors. The solar reflectors, by giving an added "push" to the process of vaporizing the mercury, unquestionably added to the overall efficiency of the plant, but it cannot be considered a "continuous action" solar power plant, nor even a 100 percent solar power plant.

A metal vapor system analogous to Krenn's has been reported by NASA in its experimental work with a 3-kilowatt mercury vapor turbine system and a 15-kilowatt rubidium vapor system [20].

One of the earliest solar heat water pumping systems proposed and placed in operation is reproduced in Fig. 34. This unit,

Fig. 34. Drawing of an 1885 solar water pumping system, France [13, 97].

constructed in 1885 in France, consisted of flat metallic hollow plates (1 to 10), which formed a portion of a shed roof tilted to an angle favorable for collection of solar energy. A volatile liquid, such as ammonia, was evaporated and generated pressure was applied to one side of a rubber diaphragm contained in a hollow sphere located in tank R. Through proper valving and cyclic operation, this diaphragm acted as a water pump, as evidence by the water jet G. Little performance data are available, but it is stated that in operation the pump was found capable of discharging 300 gallons of water per hour to an unstated height [13, 97].

One of the most spectacular early solar engines was constructed in 1901 by Frank Shuman. This was the famous Pasadena Ostrich Farm solar motor (Fig. 35). The truncated cone collector was shifted by an elaborate mechanism to track the sun, and focused on a steam generator, which when connected to its engine, developed over 4 horsepower and pumped a maximum of 1400 gallons per minute [13].

Encouraged by his success, Shuman built a second solar motor in 1907-1908 outside of Philadelphia (Fig. 36). This plant consisted of a flat-plate collector, low pressure steam engine, steam condenser, and various auxiliary motors. The entire collector of 900 square feet was placed

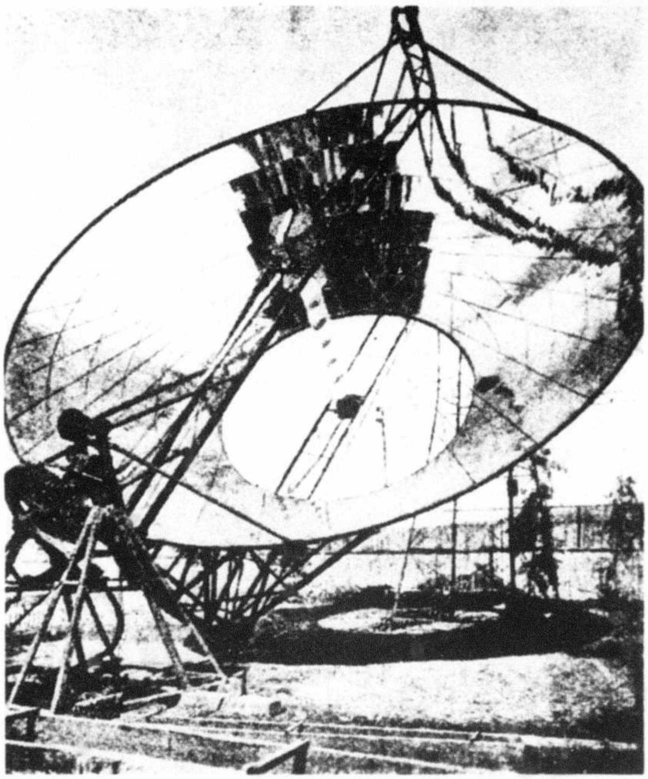

Fig. 35. Pasadena Ostrich Farm solar plant, 1901 [13].

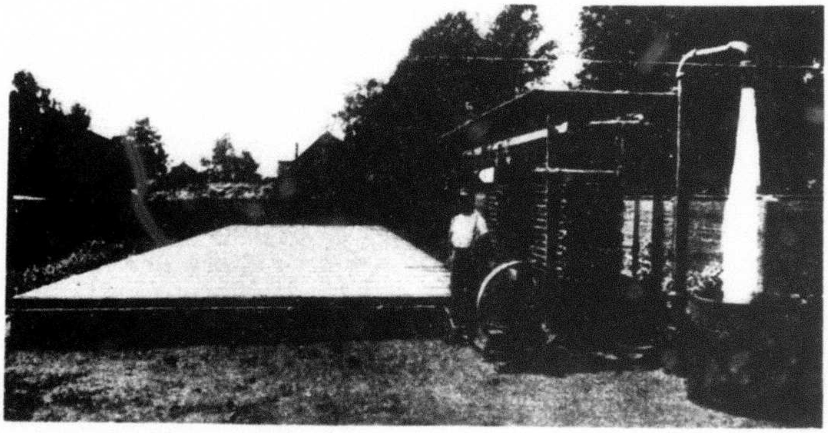

Fig. 36. Shuman solar power water pumping system [13].

at the bottom of a large wooden box covered, greenhouse style, by double layer glass plates, separated by a one-inch sealed air space. This system through a vertical single cylinder engine developed about 3.5 horsepower with a boiler temperature of approximately 93 to 99$^{\circ}$ C, and a pumping capacity of 3600 gallons per minute [20].

In 1913, Shuman, assisted by Sir Charles V. Boys of London, erected an improved solar power plant at Meidi, near Cairo, Egypt, (Fig. 37)

Fig. 37. Shuman-Boys power plant at Meidi, Egypt [13].

to provide irrigation water from the Nile for the surrounding desert area [20]. This system consisted of a series of 205-foot-long parabolic collectors having a total of over 13,000 square feet of solar interception area. The sun was focused on a series of small interconnected steam generating elements with steam piped to a 100 horsepower engine [13].

Turning now to present-day solar engine projects, we might mention India first of all, because the mass production of small solar motors, costing about $20 each, is being planned there. These motors are intended for household use, and are to work on the principle of plane solar mirrors. The design calls for a total reflecting surface of 150 square feet, which will produce the same amount of solar power as a parabolic reflector with a diameter of 7.8 feet [20].

India has also been performing a number of interesting experiments on hot-air engines driven by solar collector systems. In one, a small open-cycle hot-air engine system develops fractional horsepower when supplied with solar energy concentrated through a paraboloid reflector. This engine has been run at temperatures as high as 650° C, but materials were not available which would withstand these temperatures for long. One of the engines of the National Physical Laboratory at New Delhi is shown in Fig. 38.

The University of Genoa, Italy, has been experimenting with new collectors of solar radiant energy suitable for use as a source of thermal energy for a solar motor [52]. The collector (Fig. 39) consists of three coaxial conical frusta which, starting at a diameter of 3.20 m, concentrate the radiant energy on a beehive type collector 0.80 m in diameter at a theoretical concentration ratio of 16:1.

Fig. 38. Solar collector and hot air engine, New Delhi [13].

The beehive collector, of a selective transparency type, consists of almost 2000 glass tubes 14-15 mm in diameter, 250 mm long and 0.2-0.3 mm thick, suitably arranged and placed on the plate, which operates as both heat receiver and heat exchanger. The glass tubes are enclosed in a cylinder with reflecting walls. To prevent absorption losses, the entire face of the glass plate turned toward the sun is spirally

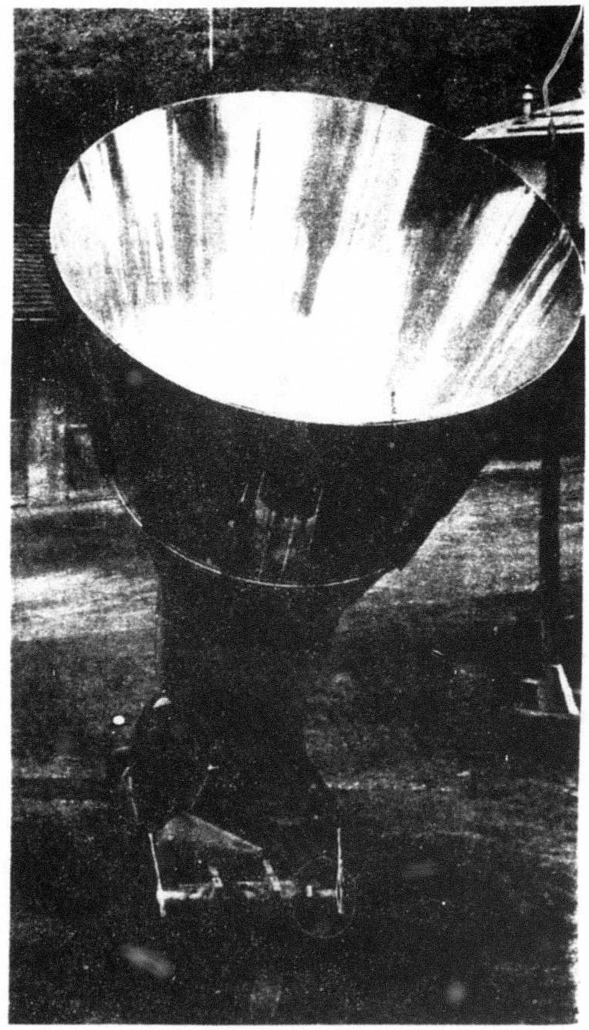

Fig. 39. Solar collector of University of Genoa [52].

grooved, like a phonograph record, in order to force the rays of incident energy to undergo a number of reflections sufficient to ensure almost total absorption.

This collector, which may be economical enough for industrial production, is able to operate at high efficiencies at temperatures of 400-500° C, supplying 5-7 kg/h of superheated steam at 450° C and 150 atm. Temperatures of this order are today considered as very good for converting thermal into mechanical energy in the steam engine [52].

A water pump, developed also in Italy, (Fig. 40) is operated with a standard Rankine vapor cycle heat engine using sulfur dioxide as the working medium [13]. Sulfur dioxide is vaporized in the flat plate collector

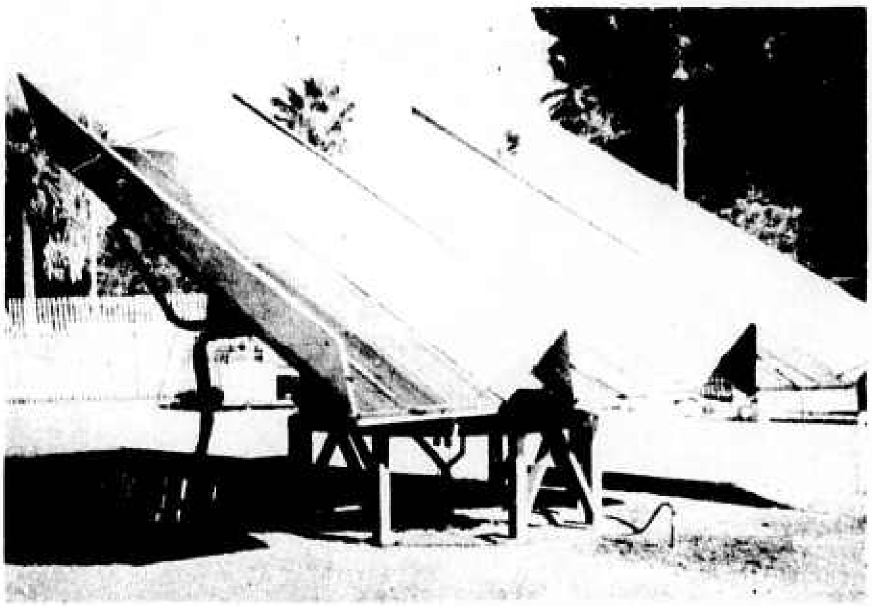

Fig. 40. Somor solar water pump, Italy [13].

and this vapor is used to drive the engine. The power so developed may be used to generate electricity or to pump water. This Somor 2.5 horsepower solar engine system is manufactured by the Societa Motori Recuperi of Lecco, Italy.

Possibly the most significant recent development, reported from Israel, is a small turbine based on a new type of collector and turbine operating with a heavy fluid (monochlorbenzene) having a lower boiling point than water [3]. In this power "package", with a capacity of from two to ten kilowatts, the turbine achieves an efficiency of 15 to 20 per cent, or three times that of conventional small steam engines and turbines; the solar collectors, in units twelve meters long, are in the form of inflated plastic cylinders, half of whose inside surface is aluminized to focus the radiation on a selective black receiver tube running through the cylinder to a heat storage system providing a constant temperature (150° C) for the turbine. During the night, it operates at a reduced load. As suggested, perhaps even simple flat plate collectors can become adequate in harnessing solar radiation to drive solar engines economically, if one not only substitutes a heavy fluid with low boiling point for water but puts together with water an immiscible secondary fluid evaporating at a lower temperature and drawing heat from the water acting as a large heat exchanger contact surface in the "boiler". After going through and driving the engine, the vapor is cooled and condensed by pumped water and returned to the collector in a closed system [3].

A new type of a solar power plant designed and patented in France affords considerable interest. This plant uses solar energy for producing a hot air current to operate a capsule type turbogenerator

unit (Fig. 41). It can be constructed on southern or southwestern slopes of a mountain ridge at an estimated relatively low cost.

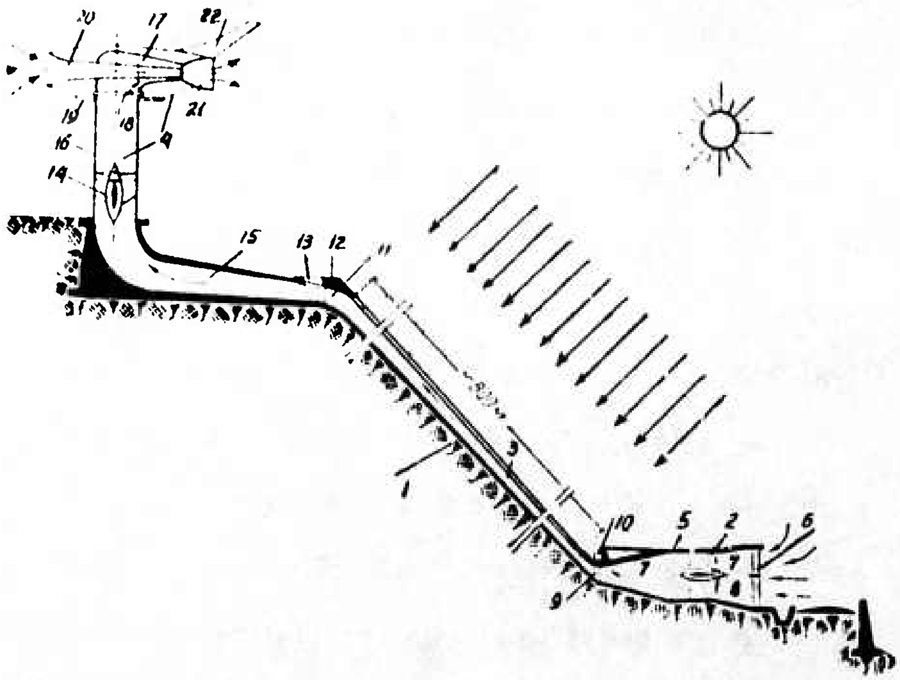

Fig. 41. Schematic of French solar electric plant operating on ascending hot air current [37].

1- hill slope; 2- lower station; 3- solar heater; 4- upper station; 5- basic unit; 6- guard net; 7- air intake; 8- small air turbine; 9- set of ducts; 10- drain pipe; 11- collector ducts; 12- platform; 13- shutters; 14- capsule type turbine-generator unit; 15- main channel; 16- vertical wind tunnel; 17- casing; 18- exhaust tunnel; 19- platform; 20- intake nozzle; 21- exhaust opening; 22- aileron.

The operation of this solar electric power plant is based on using an ascending hot air current heated by a solar heater located at the slope bottom. From the heater the hot air is forced into a wind tunnel located on the top of the slope; the wind tunnel is equipped with a capsule type turbine-generator unit.

The power station consists of a lower and an upper station. The lower station, located in a valley, is equipped with an air intake and a solar heater placed on the hill slope at 45°. In the upper station the capsule type turbine-generator unit is installed. It is desirable to put a rotating air ejector at the outlet part of this unit to use supplementary wind energy for intensifying the suction effect of the turbine, i.e., to increase the speed of air flow over the turbine blades.

The solar heater consists of ducts placed between metallic elements whose sun-exposed sides are blackened. It is mounted on supporting rib-like struts, placed along the slope under glass cover which provides a greenhouse effect.

A more detailed description of the operation is given in [37] as follows. The lower station (2) contains the basic unit (5) consisting of three air intakes protected by guard nets (6). In some cases it could be advantageous to place in each duct of the air intake (7) a small air turbine (8) to assist the secondary generator. Behind the air propellers, the air intakes transform into a set of ducts (9) which form the solar heater (3). Under the heater is a drain pipe (10) for collecting the condensed water accumulated on the glass covering the heater, which is channeled away through drainage chutes.

The solar heater has a reinforced concrete base with vertical corrugated walls along the slope, forming a series of ducts for circulating heated air; up to forty ducts may be used for the purpose. The wall tops have special devices to fasten the duct covering glass, and rails for repair carts. The edges of glass plates, perpendicular to the ducts, overlap each other and are sealed by polyethylene packing. The beds of the ducts have stationary reflection and heat insulators, composed of fiberglass and elastic polystyrene which are covered by polished aluminum plates extending along the bottom part of the corrugated walls. The corrugated walls also support the transverse spacer tubes on which are suspended corrugated aluminum sections acting as heat absorbers and solar radiation exchangers. These sections on the outer surface are blackened (oxidized or anodized) to improve radiation absorption; on the inside they are polished to counteract thermal radiation emanating from the duct bottom. Sections are mounted along the entire length of the ducts in such a way as to increase the air flow turbulence and heat.

All ducts forming the solar heater are integrated into several groups (11) under platform (12). The ducts are equipped with shutters (13) for cutting off the air during repair or inspection of the turbogenerator unit (14). The ducts (11) are connected via main channel (15) with vertical wind tunnel (16) where the turbogenerator unit (14) is mounted. The wind tunnel, owing to its casing (17) design, forms a Venturi tube with exhaust tunnel (18) and

exhaust opening (21) for evacuating the ascending hot air. In the upper portion of the wind tunnel (16), there is a round platform (19) on rails for turning the intake nozzle (20) toward the prevailing winds to generate a vacuum and thus enhance the turbine performance. The aileron (22) is provided with an aerodynamic balancer which controls the motors for guiding the intake nozzle (20) to windward. As soon as the sun warms up the air in the solar heater (3), the ascending flow of hot air pulls in fresh air and activates the small air turbine (8). Assisted by winds entering the intake nozzle (20), the capsule type turbine-generator unit (14) is activated.

The designers note that several such solar power plants could be constructed in parallel, creating a large industrial complex [37].

Generally speaking, the solar collector used to supply energy to an engine system may be either of the flat plate of "hot-box" nonconcentrating type, or of the parabolic or semiparabolic concentrating type. Simple concentrators may also be used together with flat plate collectors in order to increase the collection area and intensify the radiation received. From the collector the heat must be transferred to an engine by a working medium such as steam, heated air, or other fluid which stores the heat either by an increase in temperature or by a phase change. Once the heat is collected and transferred to the engine, another working medium more suitable for the power cycle will be involved in the heat engine itself. From the heat engine a portion of the heat is then rejected to the ambient environment through a condenser, cooler, or radiator. Figure 42 shows schematically

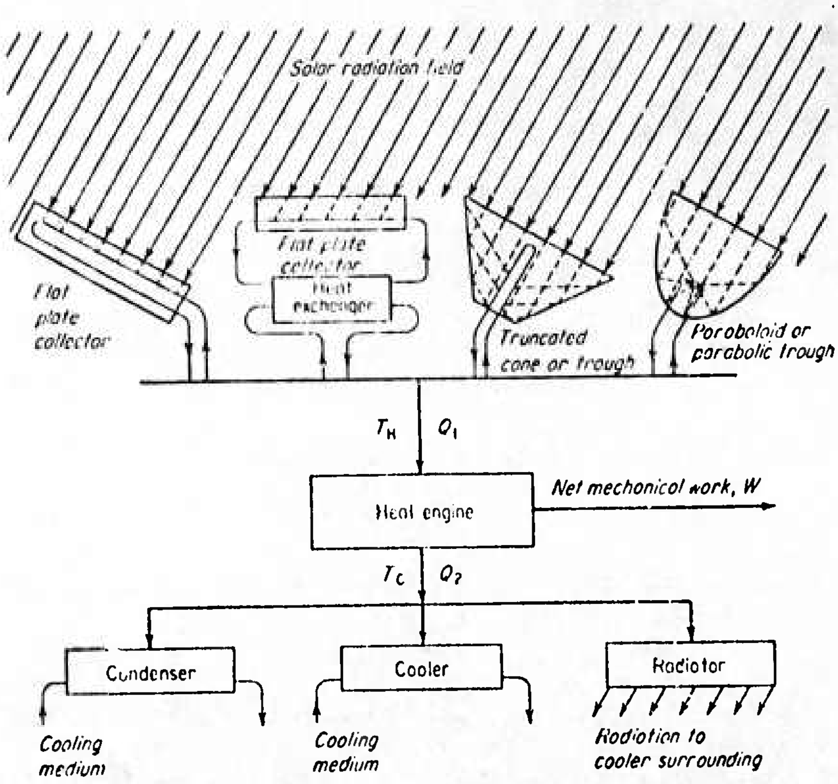


Fig. 42. Schematic of solar collector - heat engine systems [13].

most of the heat-collecting and heat-rejecting engine systems which have been used or proposed to date.

For a more detailed study of the important factors governing conversion and collection methods, we may divide systems into the following general categories [87]:

- direct receivers, oriented receivers and their heliostats,
- plane reflectors, and
- convergent reflectors.

Direct receivers, oriented receivers and their heliostats.

Direct reception has the advantage of only involving a single reflection on the mirrors that concentrate the radiation. The principal disadvantage of this type is that the axis of convergence of the radiation is displaced in space, and the focus, located on this axis, is also displaced in space. This arrangement is also unfavorable, since the convergent radiation attacks substances from down to up, or laterally, and it is difficult to perform certain operations, for instance melting, with such apparatus. On the other hand, for operations on solid surfaces, reaction between gases, cracking, etc., direct reception is the simplest method. In some assemblies, the image of the sun is reflected downward by means of a plane mirror placed in the path of the convergent rays. It should also be noted that direct reception is more favorable for apparatus with a smaller aperture than paraboloids, or those using lenses.

The reception of solar radiation by a plane orienting mirror. followed by a fixed parabolic mirror, was first put into practice by Conn, and later by the Mont-Louis Laboratory [87]. This method can now be generalized for most laboratory devices and large-scale installations. It has the considerable advantage of having a fixed focus of orientation, whether horizontal, vertical or inclined, which may be selected according to the operation being performed.

In order to keep the optical axis of direct receivers pointing toward the sun, they may be guided either by an astronomical method or by a photosensitive control mechanism. Thus some installations are mounted on an equatorial axis whose motion is controlled by an astronomical clock. This method has the advantage of holding the axis of the paraboloid in the direction of the sun, even if the solar radiation is briefly interrupted by clouds. The declination of the mirror has to be adjusted daily by hand. It appears that this method of control would be rather expensive for large machines. The collector mirrors are often automatically trained on the sun by using an auxiliary lens with its optical axis parallel to that of the paraboloid. Typically, a circular screen located in the focal plane is surrounded by four control photocells or transistors operating in pairs to control the two directions in elevation and the two directions in azimuth. A slight displacement of the solar image off of screen center illuminates one or two of the control photocells. This arrangement has been universally adopted for guidance of direct receivers or to control the motion of heliostats. [87].

Heliostats (clock-driven mirrors) are guided by a control system (lens, screen, and framing cells) located in the path of the reflected radiation. This control arrangement is fixed, and the direction from the lens to the screen center defines the direction of the reflected radiation. The photocell currents may be used in various ways to cause motion of the heliostat or the direct reception devices. The first Mont-Louis model controlled electric motors by means of a series of contacts of decreasing

sensitivity, which initiated the operation, in either direction, of asynchronous motors, one adjusting the elevation, the other the azimuth of the heliostat. Parallel developments in different countries (United States, USSR, France, Japan, Israel, etc.) today employ the following general sequence: current from a photosensor, electronic amplification of this current, control of the excitation of a dynamo (of amplidyne type or similar device), direct current generated by the dynamo, running a reversible direct current motor. This electrical command system permits command of simultaneous motion of a certain number of heliostats controlled by a master heliostat using mechanical coupling. Mechanical coupling can ensure excellent accuracy of control if the transmission shafts run at adequate rotary speed. It should also be mentioned that certain devices do not include an electric motor for aligning the machines. Here the amplified photocell currents act to change the position of distributor slides or servovalves, admitting oil under pressure into double action hydraulic jacks, one controlling the elevation and the other the azimuth. As before, two elevation photocells, upper and lower, act on the two faces of the same actuating cylinder, while two azimuth photocells, right and left, act on the second cylinder. The axes of rotation of heliostats are in general perpendicular. Such a system is used to operate the 63 heliostats of the 1000 kw solar furnace at Odeillo-Fort-Romeu, France [87].

Plane reflectors - Various experiments have shown that for long distance reflections, glass surfaces coated on front or rear faces with metallic reflectors give good results; they appear to be better than reflectors made of polished metal planes. Metallized plexiglass or metallized plastic film stretched on metal frames do not seem to have been tried for long-distance plane reflection.

The majority of heliostats use surfaces of metallized glass. Some French and U. S. installations use reflection from the rear surface after passing through the glass. The thickness and transparency of the glass are thus very important for the efficiency of the plane reflection. On the other hand, the mounting of the glass must be substantially plane for the various positions assumed by the heliostat. The thickness permitting this result will naturally be greater, the larger the elementary surface itself. Moreover, to avoid losses of light at the glass interfaces, it is better to use maximum dimensions.

Another class of plane reflectors consists of glass surfaces coated on the front face with thermally deposited aluminum. Owing to their high reflectivity, these surfaces were adopted for the large solar furnace at Sendai, Japan with the following details: a glass mirror 90 x 100 cm, 10 mm thick, with silvered or aluminized rear face, had a reflection factor of 67 percent for an incident ray at $15^{\circ}$ inclination, and one of 56 percent for an incident ray of $40^{\circ}$. The aluminum deposit under the same conditions give 95 and 92 percent respectively. Aluminum surfaces have

the important advantage, especially for photochemical reactions, of reflecting solar ultraviolet radiation. On the other hand, their resistance to bad weather is questionable. This resistance is improved by a protective deposit of silicon monoxide [87].

Another factor to be considered is the resistance of glass to thermal shock and mechanical stress. Experience shows that glass sheets 1 x 1 m by 1 cm thick are much more fragile, thermally and mechanically, than glass plates 50 x 50 cm but less thick.

In the use of plane reflection, considerable attention should be given to the relative increase in the penumbral zones with increasing distance between the heliostat and the parabolic reflector. These zones act only on the outer contours of the reflected nappes. The surfaces of the parabolic reflector must be inside this aureole of decreasing energy.

Convergent reflectors - The problem of creating reflecting or refracting surfaces has various solutions, such as the large aperture which is necessary to get appropriate accumulation of energy; this practically rules out the use of lenses, which are considerably more expensive than mirrors. (The only solar furnace that uses lenses today is at the California Institute of Technology. It employs a combination of refraction and plane reflection to increase the angle of convergence).

For small mirrors, the reflecting surface is usually in a single piece. The first laboratory solar furnaces made extensive use of military antiaircraft mirrors. Such mirrors, 1.5 to 2 m in diameter, are made either of special white glass, silvered on the rear face, or of a polished alloy. Because of the severity of the original specifications, their optical quality is entirely adequate for high concentration of energy. They are valuable for fundamental research with either solar furnaces or image furnaces.

Light aluminum mirrors, about 10 m in diameter, appear to have the optical qualities of smaller mirrors and they do constitute an interesting and economical solution for moderate concentration of useful amounts of energy. The aluminum sheets may be fabricated by drawing or explosive forming. Another interesting solution for small and medium size equipment is the use of plastics. Parabolic plastic molds have been produced by solidification of a plastic resin on a mercury surface rotating at constant velocity. The use of aluminized Mylar on a polyurethane mold also gives mirrors of good optical quality [87].

Spherical or parabolic reflectors provide the maximum concentration of solar radiation in engines or cookers. Spherical reflectors with a large bending radius must, when applied to solar cookers, be equipped with a device for supporting the cooking compartment at exactly the right distance from the geometric center of the reflector, otherwise the

compartment will not be "in focus", and the rays will be spread out over too large an area to provide maximum heating of the container. When the image area is large, it frequently happens that the bottom of the cooker (if it is of normal size) gets out of focus, so that frequent adjustment of the reflector becomes necessary. Some models are equipped with automatic devices for keeping the food container continuously in focus.

A parabolic reflector does not have these disadvantages, since the image it produces is clear, small and sharp. The astigmatism of the parabolic reflector is greater than that of the spherical reflector, but because the image is so much smaller, it stays in focus much longer. For this reason, as well as for the fact that it is much easier to handle, the parabolic reflector must be considered the better of the two types.

Some data on the reflective power of various materials are given in the following table:

| Material | Reflectivity, percent |
|---|---|
| Aluminum, high-purity | 89 |
| Aluminum, commercial grade | 74-85 |
| Chromium | 51 |
| Constantan (60 Cu, 40 Ni) | 64 |
| Copper, polished or burnished | 82 |

| | |
|---|---|
| Duralumin | 53 |
| Glass, silvered | 88 |
| Magnalium (69 Al, 31 Mg) | 74 |
| Mercury-bismuth amalgam | 72 |
| Nickel, polished | 60 |
| Silver-plated metal (electrodeposited) | 96 |
| Speculum (68 Cu, 32 Sn) | 66 |
| Steel, soft | 58 |
| chrome-plated | 54 |
| galvanized | 64 |
| silver-plated | 91 |
| tinned | 49 |
| Zinc, polished | 54 |

Aluminum foil, which besides being inexpensive has a high reflectivity (70-85 percent), has not proven successful as a coating for reflectors, perhaps because of its much greater heat absorption and transmission [20].

In considering the overall problem one should bear in mind that the conversion of solar energy to mechanical power involves some inherent thermodynamic limitations such as the maximum theoretical efficiency which can be attained by any heat engine operating between two temperatures.

In addition to such fundamental barriers, there are others more transient in nature which may be subject to improvement through development of components and systems. Methods of fabricating cheaper and more efficient collectors, for example, will permit the construction of solar-mechanical conversion systems of greater economy [13].

Experience to date indicates that the two most interesting possibilities for the development of solar engines using currently well defined cycles appear to be for engines operating on a vapor or hot air cycle. The working medium itself poses no problem as far as the hot air engine cycle is concerned. Here the problems lie in the development of mechanical and thermodynamic systems capable of reproducing the high efficiencies inherent at high operating temperatures. Specific problems involve the elimination of overlapping parts of the cycle, the development of regenerative heat exchangers of high efficiency, and the metallurgical development of materials capable of withstanding the high temperatures encountered in the operation of hot air engines.

Solar engines cannot now compete with gasoline engines or electric motors, but they can probably find a place where cheap fuel is not available. Steam engines appear to be the most likely to succeed, but research should consider also hot air and vapor engines operating on low boiling liquids. An example of this type based on ethyl chloride is proposed in [104]. Low capital investment and simplicity of operation are the criteria in the localities where solar engines are needed now [9].

Small 1-horsepower gasoline engines are available for around $50, but 1-horsepower steam engines are difficult to obtain and cost five to ten times as much. Apparently there is no fundamental reason why the steam engine has to cost much more; if there were sufficient demand for steam engines, they could probably be mass-produced as cheaply as gasoline engines. There is a great demand in nonindustrialized areas for more power, and intense efforts should be directed toward the development of small, cheap steam engines perhaps of radically new designs and materials. A goal might be to produce a 1-horsepower engine for $50, a movable focusing reflector or a stationary nonfocusing heat trap of over 150 square feet for $50, and a boiler and various accessories for $50, making a total of $150 [9].

The gas turbine cycle would appear to be adaptable to high temperature operation with large scale equipment, but it appears most likely that solar power systems will be developed primarily for small scale application for use in remote areas where large scale power is not found. Over the past three decades many new working media which might be adaptable to vapor cycle engines have been developed, and they should be fully explored. It seems nevertheless inherent that water and air remain the two simplest media for adaptation to heat engine cycles [13].

In summary we can say that a solar machine, specifically a thermal machine driven by solar heat, cannot compete with traditional type energies wherever these are available at normal costs, inasmuch as solar energy presents conspicuous disadvantages, such as intermittence and storage problems. Solar energy, however, offers one great advantage as compared with traditional type energies: it is free and neither requires a distribution system nor transportation from the source. In other words, it can effectively substitute for other forms of energy whenever distribution costs to the site of the latter become prohibitive.

In analyzing the feasibility of converting solar power, Tabor [103] considers solar power units divided into three classes: midget, small and large. The first represents a power supply of a few watts, the second being in the kilowatt range (from a fraction of a kw to several kw), and the third in the megawatt range.

For power range of a few watts it is almost certain that the mechanical heat engine would not be considered and only static systems (i.e. without moving parts) would come into question. This would include photoelectric cells and thermoelectric and thermionic generators.

The kilowatt and megawatt solar units would have certain common problems as well as fundamental differences. The megawatt units imply central power production and a power distribution network, and they would involve very large areas of solar collection, so that if any conventional collector is considered, the maintenance problem may be

insuperable. Because the megawatt unit involves a distribution system, the cost of power must be considerably lower than for a kilowatt unit that may be located in any remote place. In addition, to provide a steady supply, storage is a virtual necessity for a megawatt unit, whereas the kilowatt unit may be used in many cases without storage, as for example when used for water pumping.

Because of these differences, most proposals for solar power units have been in the kilowatt class with only a very few suggestions for the megawatt sizes.

The interconnection between engine and collector is further related to a fundamental policy question, i.e., whether to have a high efficiency system with expensive engine and collectors or a low efficiency system with low-cost components. If we speak of kilowatt plants, the collector is likely to be the most expensive item. In this case, suggestions are for making the heat engine as efficient as possible with a moderate operating temperature, in order to keep the size of the collector down. A stationary cylindrical parabolic collector is envisaged with operating temperature ranging between 150 and 200° C. On the other hand, there are different views that the cheapest possible collector should be without cover glass or insulation, operating at a low temperature ranging between 40 and 50° C [103].

For operating temperatures below 100° C it is possible to consider stationary nonfocusing collectors. Apart from the advantages of being stationary and having no mirror surfaces that might distort or deteriorate, these collectors exploit diffuse radiation as well as the direct solar radiation. For operating temperatures between 100 and 200° C, stationary focusing collectors of low concentration power are required. Such collectors require their tilt to be varied according to the seasons, but this is far less complicated than a sun tracking mechanism.

For operating temperatures above 200° C, focusing collectors which track the sun are required, and for temperatures much above 200° C the mirror must be paraboloidal rather than cylindrical parabolic. Tracking collectors have the advantage that they "see" more sunshine than a fixed collector (about 40 percent more) but the tracking mechanism for a large area collector is extremely expensive because of the wind forces. Double curvature mirrors are so expensive that they would be impractical for terrestrial power application except in the midget sizes.

Tabor also notes that the heat engine is the only instance where the kilowatt unit is at a serious disadvantage versus the megawatt unit. For the megawatt unit, turbines (usually steam) can be built that reach 60 percent of the Carnot efficiency or better, whatever temperature

range is considered, whereas small steam engines and turbines in the kilowatt size are notably inefficient. However, if high molecular weight fluids having certain specific characteristics are employed instead of steam, there is a great chance of producing kilowatt turbines with almost the same efficiency as megawatt units. With operating temperatures of 150-200° C, turbine efficiencies of 15-20% for a 2-10 kw unit are anticipated. This relatively high efficiency would even permit the turbine to be fuel-operated economically during cloudy periods. Hence we can say that the development of an efficient small prime mover operating at moderate temperatures would represent a major step forward in the realization of practical kilowattt solar energy power packages [103].

Consequently, for sizes in the range of a few kilowatts, there are good prospects of getting cheap solar power in the near future in a sunny climate using realistic interest and amortisation charges but avoiding maintenance and operating costs. This again implies the use of high efficiency heavy vapor turbines and collectors operating at about 150-200° C. Lower power cost can only come if the longevity of the collectors can be increased without a corresponding increase in their capital cost. For large central power units in the megawatt class, a lower power price is essential andcompletely different types of collectors, of an order of magnitude cheaper per unit area, must be evolved [103].

# IV

# PRACTICAL APPLICATIONS OF SOLAR ENERGY

## A. Solar Furnaces for High-Temperature Processing

A solar furnace is more exactly an optical system in which the solar radiation received by a collector is concentrated onto a small area. When this highly concentrated radiant energy is received into a cavity, intense heat is generated. This cavity, which is really the furnace, is a minor part of the whole system; a solar furnace should properly be called a solar energy concentrator.

In the 17th and 18th centuries both mirrors and lenses were used, and in 1772 Lavoisier built a furnace with a collecting lens of about 5 ft in diameter, in which he almost reached the melting point of platinum (1773$^\circ$ C). After Lavoisier, solar furnaces were completely neglected until the beginning of the 20th century. In 1921, Straubel and associates at the Zeiss Company in Germany constructed the first modern furnace of the reflecting type. With a glass parabolic mirror of about 6 ft. in diameter and a focal length of 2 feet, they reached temperatures of more than 3000$^\circ$ C. Since that time parabolic mirrors of various diameters have been used.

Between 1930 and 1932 a lens furnace was built at the California Institute of Technology at Pasadena, by George Hale and associates, with the objective of achieving a high-temperature source for spectroscopic studies. Since then, however, it has become apparent that furnaces of the reflector type are easier to build and more practical than those of the refractor (lens) type [12].

Solar furnaces are presently used predominantly for materials testing and research purposes. For these applications, small solar furnaces have been sufficient because the temperatures achieved depend mainly on the quality of the installation, and not on its size.

For more practical applications, much attention has been focused on the possibilities of using solar furnaces for small-scale refining of minerals and for certain chemical processes. Here, the solar furnace can be used to treat and produce a variety of materials, pure chemicals, single crystals, and pure or rare metals. The solar furnace, besides reaching high temperatures quickly, is specially advantageous due to the absence of contamination by combustion products or electrical resistance wires, thus permitting the preparation of pure high-quality products. However, the solar furnace has limitations due to the intermittence of sunshine, which reduces the plant operating time by more than half over a year [3].

Despite the fact that solar energy is of low intensity, solar furnaces are capable of providing temperatures higher than can be obtained in fuel-fired and most electric furnaces. The focused light can be shifted quickly to get very rapid changes in temperature, which is useful in studying the properties of special materials under extreme temperatures. The attainment of very high temperatures is not limited to small research furnaces. Large furnaces, 30 feet or more in diameter, with perfect optical surfaces can be used for melting many pounds of refractories at one time [9].

Solar furnaces have proven their value in research and in the industrial-scale production of expensive, high-purity materials. Material processing can be performed in uncontaminated conditions in ambient air, as well as in controlled or inert atmospheres, when sealed in glass or plastic containers [20].

Considerable advances have been made in the technology and operation of solar furnaces. However, there are numerous problems to be solved, such as the type and construction of the concentrator and sun tracking system, the arrangements of the receiver or furnace proper (direct reception, cavity, etc.), and the choice of construction materials. In large furnaces, a stationary concentrator is used in order to keep the furnace target in a fixed position, while radiation is reflected onto the concentrator by large plane mirror assemblies (heliostats) tracking the sun. Small systems require only one set of reflectors which are made of hard, lightweight plastics spun into the desired shape. Stimulated by space research, considerable progress has also been made in the use of aluminum, which has certain advantages over glass mirrors, for example, in the reflection of ultraviolet radiation useful in photochemical reactions, as distinct from heat applications [3].

The problem posed by the design of large solar furnaces with high concentration of energy is the reflector element, whether used in

concentric rings, or in horizontal alignment on mountings, to form the paraboloid. Each of the large solar furnaces that have been built or are now under construction has embodied a different solution to this problem.

There are numerous ways of collecting the solar energy at the focus; these methods may be reduced to a number of typical operating patterns. Direct collection of solar energy and treatment at the focus, on horizontal, vertical or inclined surfaces is common practice. For example, a self-supporting body may be treated on a horizontal surface; this is the typical operation in an oxidizing medium and involves no contamination of the substances treated. The efficiency of this procedure may be improved by displacing the substance being irradiated in order to obtain belts of melted or fritted products in various shapes.

Direct treatment may be applied to solid specimens, for instance to rods held vertically at each end, practically collinear with the focal axis of the optical system. By shifting the rod in the direction of the focal axis, a molten zone may be made to migrate from one end of the rod to the other. This method may also be used when the rod is supported laterally by cooled jaws.

Another version of direct treatment permitting handling of practically all the substance, without contamination, is by heating the material on a metal plate (aluminum or copper) of high thermal conductivity, which is strongly cooled on the bottom.

All the above methods may be employed in a controlled atmosphere. The use of vacuum requires mechanically resistant and transparent walls. For small heating units, Pyrex glass and silica glass are very suitable, both being transparent to solar radiation. For large units, the problem of the transparent wall with high mechanical resistance still remains open.

Cavity reception is another method of treatment which can either obtain better yields with reflecting substances, or get more regular variations of temperature in a given operation. The cavities behave like black bodies, and their inner walls heat up uniformly, owing to the numerous internal reflections. In general, they are characterized by an internal surface much larger that the outer surface, permitting the penetration of convergent radiation.

Another type of black-body cavity represents a very interesting method where the substance, held against the furnace wall by centrifugal force, is treated without contamination. This type of furnace affords the advantages of cavity treatment and of direct treatment of a self-sustaining substance. Cavity operations may be conducted in a vacuum (for small devices) or in an inert gas. A controlled atmosphere may be realized in centrifugal furnaces by supplying the gas to the furnace interior itself.

Treatment in a cavity behaving like a black body finds application in determining the energy distribution of the solar energy on the focal plane. Black-body cavities equipped for calorimetric measurements are used to explore the focal spot at different points of its surface, since the surface of the radiation access orifice can be modified at will by interposing cooled screens which are provided with orifices of various diameters.

With this brief discussion of some furnace principles, we now examine some existing installations.

## France

The first large solar furnace, built in 1952 at Mont-Louis in the French Pyrenees (Figs. 43, 44) has a vertical parabolic concentrator 12 m in diameter mounted on a huge iron structure and can be moved horizontally and vertically. The heliostat used in conjunction with this

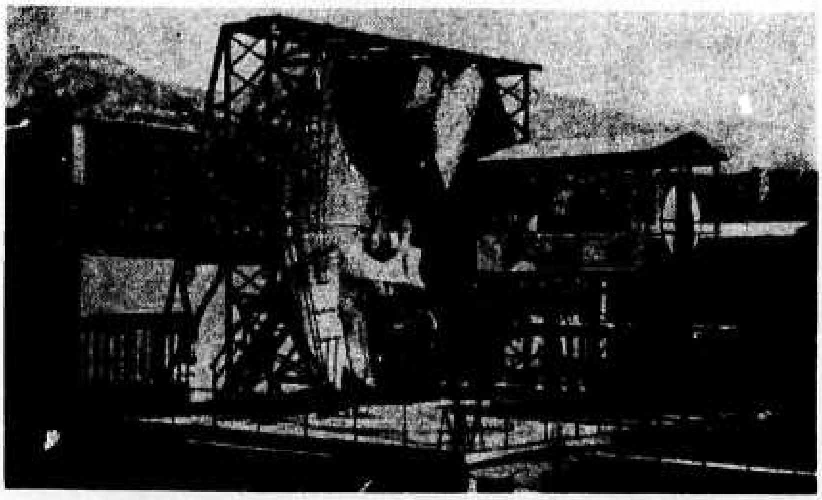

Fig. 43. Parabolic concentrator of Mont-Louis solar furnace [88].

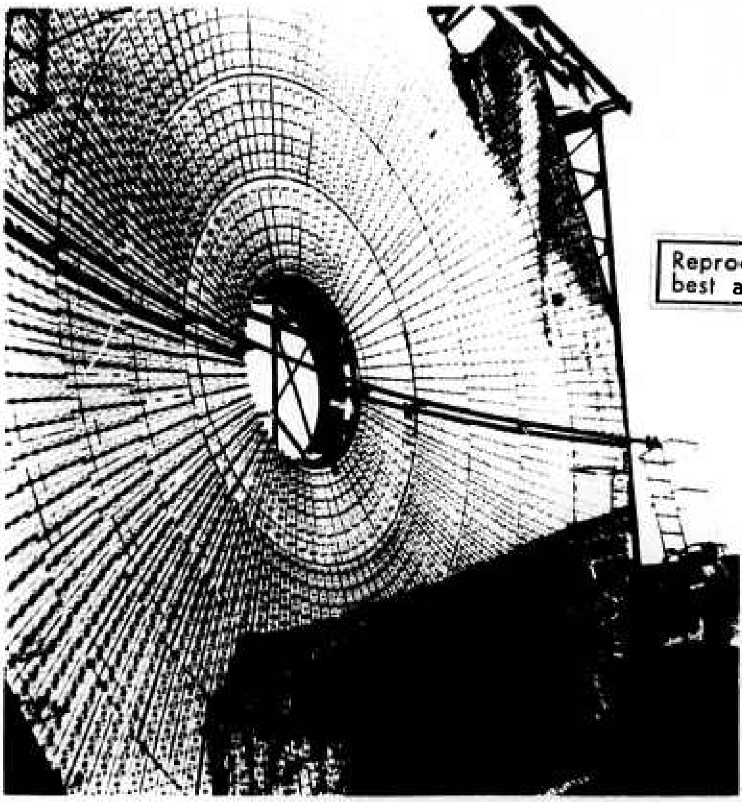



Fig. 44. Close-up of parabolic concentrator of Mont-Louis solar furnace [21].

furnace is composed of 50 x 50-cm plane mirrors, with a total area of 13 x 11 meters [88]. The parabolic concentrator is made of 3500 plates, about 3 mm thick, assembled into 130 segments and fitted into 5 concentric rings. Zenith and azimuth rotation of the system is by hydraulic drive. The thermal power of the furnace is given as 50 kilowatts equivalent [38, 88].

The largest solar furnace in the world (Figs. 45, 46, and 47) was built on a mountainside also in the Pyrenees, between the villages of


Fig. 45. View of the Odeillo solar furnace facility in France [80].

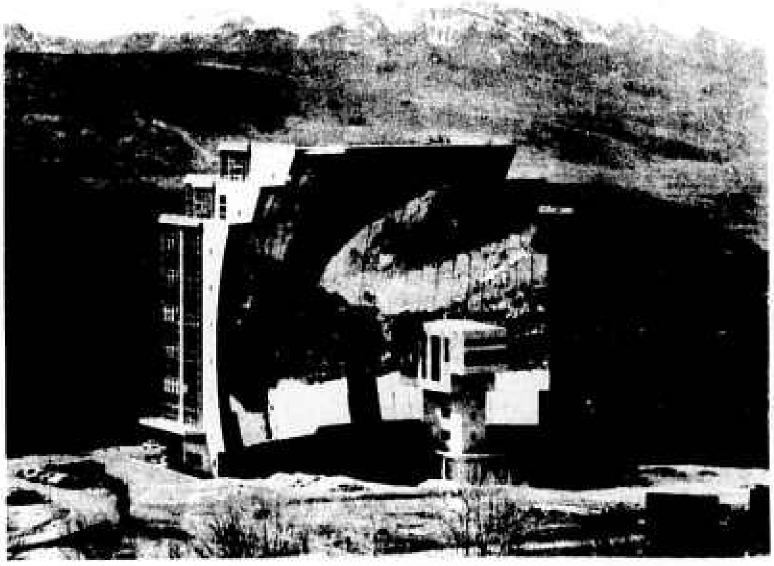

Fig. 46. The Odeillo parabolic concentrator and testing tower [97].

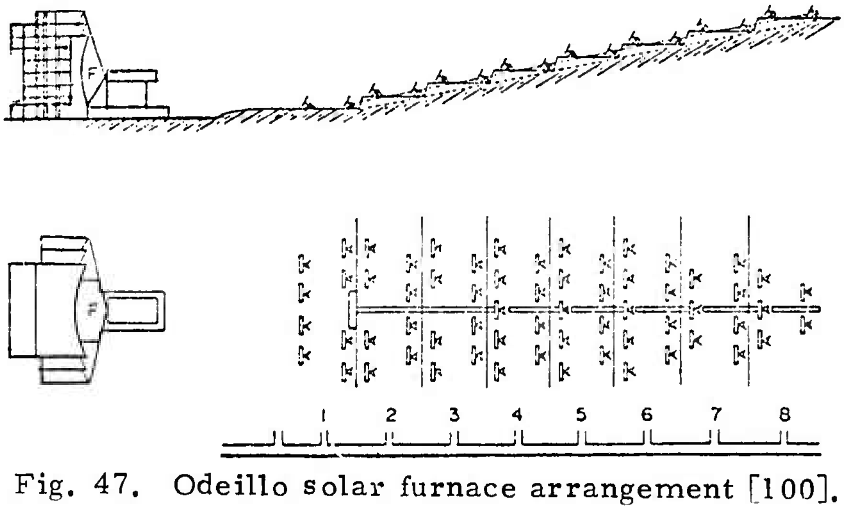


Fig. 47. Odeillo solar furnace arrangement [100].

Odeillo and Font-Romeu; this location is reported to be the sunniest area in France, averaging 250 clear days annually [38].

The parabolic concentrator, built into the wall of a 10-story structure (Figs. 46, 48), is 43 m high and 54 m wide. It consists of about 10,000 small plane facets, 4 mm thick, arranged into curved individual

Fig. 48. Close-up of the Odeillo concentrator and laboratory [88].

mirrors 50 x 50 cm in size forming a surface of 3000 $m^2$ divided into nine horizontal bands, with a focal length of 18 m [88].

The degree of paraboloid concentration is 7.75 x $10^4$ with a thermal density of 1700 $w/cm^2$ in the focus. The focal area of the furnace is centered in a metal enclosure on a tower fitted with stainless steel shutters to control the amount of solar radiation reaching the focal zone [38].

For this solar furnace, 63 plane heliostats are used (Fig. 49), each 6 m high and 7.5 m wide and containing 180 (50 x 50 cm) plane mirrors for a total reflecting surface of 2835 $m^2$. The heliostats are arranged in eight terraces and have individual sensors for automatic focusing on the concentrator [88].

The rated thermal power of this furnace is 1000 equivalent kilowatts [38]. This estimate was made after allowing for various energy losses, and assuming the intensity of incident solar radiation to be 0.1 watt/ $cm^2$, the normal level for this locality. The capacity of the furnace for fusing specific refractories at temperatures of up to 3500° C ranges between 2000 and 3000 kilograms daily [88].

To determine the efficiency of the furnace several specific tests have been conducted to study the concentrator's mirrors. These are of

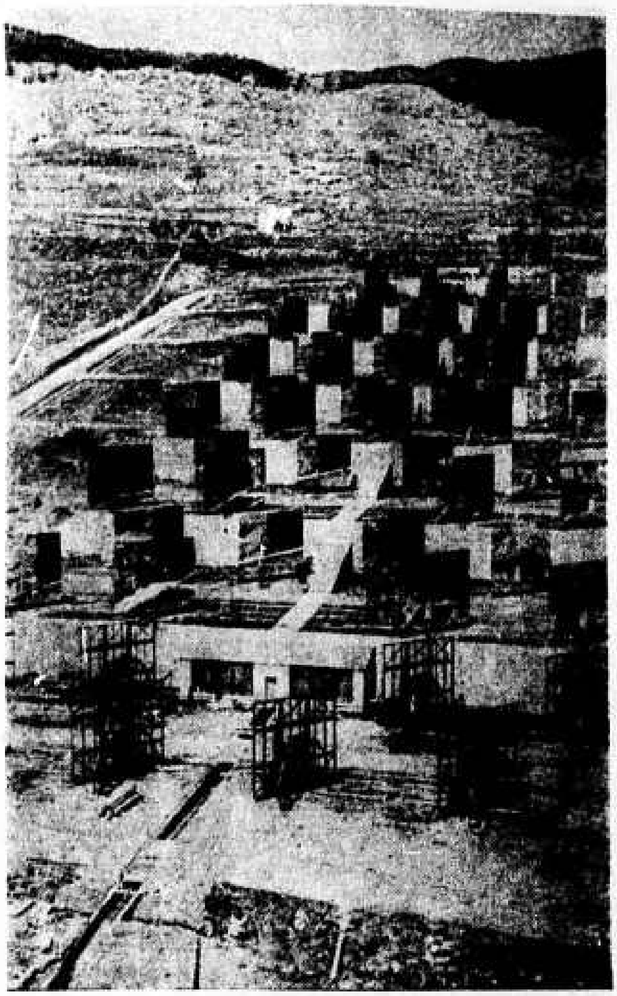

Fig. 49. Terraced heliostat field of the Odeillo solar furnace [88].

hardened glass, silvered on the rear face and designed as the elementary facets of a parabolic concentrator of 18 m focal length. The two successive reflections (once each from the heliostat and the curved mirror) plus internal absorption in the glass cause a loss of 39 percent of the incident solar radiation. Taking this energy loss into account and assuming the efficiency

to be 65 percent, the energy density at the focus of the installation will reach 1700 watt/$cm^2$ (or over 400 cal/$cm^2$/sec), corresponding to a black body temperature 3900° C. This temperature can be attained only with an ideal receiver, i.e., a disk with its front face perfectly black and its rear face perfectly polished [96].

In order to obtain a realistic appraisal of the capabilities of solar furnaces in metallurgical and chemical processing, it is necessary to perform experiments on a much larger scale than that of a research furnace intended for fundamental material studies. At the present time, only one relatively large furnace, originally conceived to cover a range of industrial applications, has been in operation long enough to have produced tangible results. The solar furnace at Odeillo is the most important in this field, and its size is sufficient for the evaluation of industrial processes [19].

As an illustration of the immense capacity of the Odeillo furnace operating with the highest temperature (3900° C) attained in solar engineering, the concentrated solar rays are capable of instantly piercing a steel alloy plate 25 to 30 centimeters thick (Fig. 50).

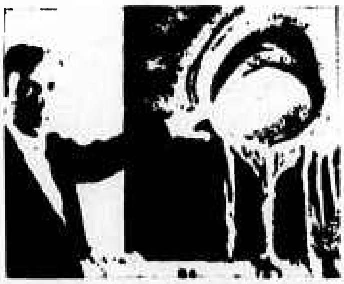

Fig. 50. Hole created by 3900° C concentrator on 25-30 cm thick steel alloy plate [70].

This solar furnace is used also for producing and studying new alloys, particularly the testing of new high-strength steels. Besides metallurgical engineering, interesting experiments in the fields of chemistry and physics are conducted on this unique installation. French solar scientists assert that this furnace makes it feasible to conduct experiments otherwise impossible in conventional laboratories [70].

Algeria

The third largest solar furnace in the world (Fig. 51, 52) located at Bouzareah, Algeria, is being used for photochemical research and

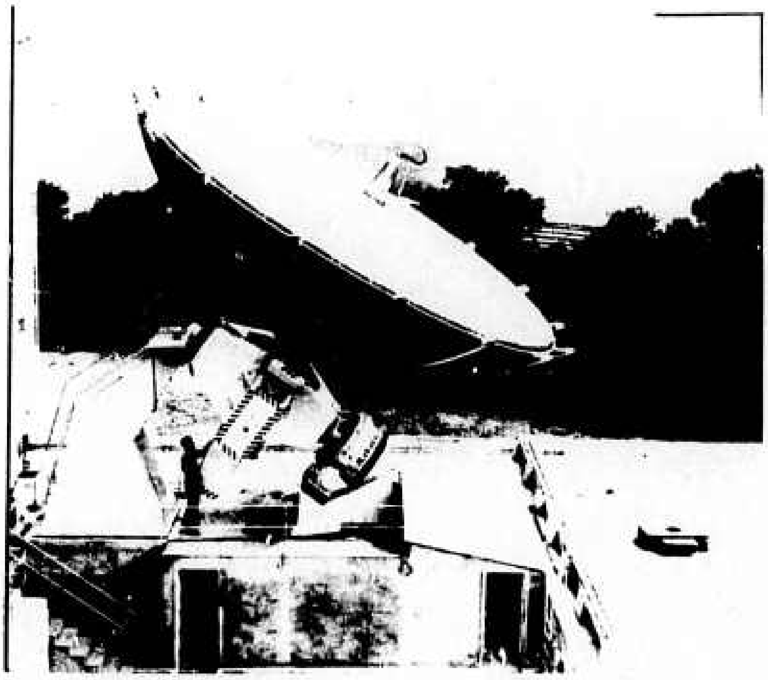

Fig. 51. Solar furnace at Bouzareah, Algeria [97].

the production of nitrogen from the atmosphere [97]. This solar furnace, also called "Heliodyne," has a parabolic concentrator 8.4 m in diameter made of precision die-forged, electropolished aluminum plate [88]. It is mounted on an equatorial axis whose motion is controlled by an astronomical clock. This method has the advantage of holding the axis of the paraboloid in the direction of sun, even if the solar radiation is briefly interrupted by a cloud.

On a clear day, the rated capacity of the Bouzareah reflector is estimated at 50 kilowatts, with a total reflective power of 82 percent. However, the problem of converting solar power into mechanical power has not been completely solved with this installation [20].

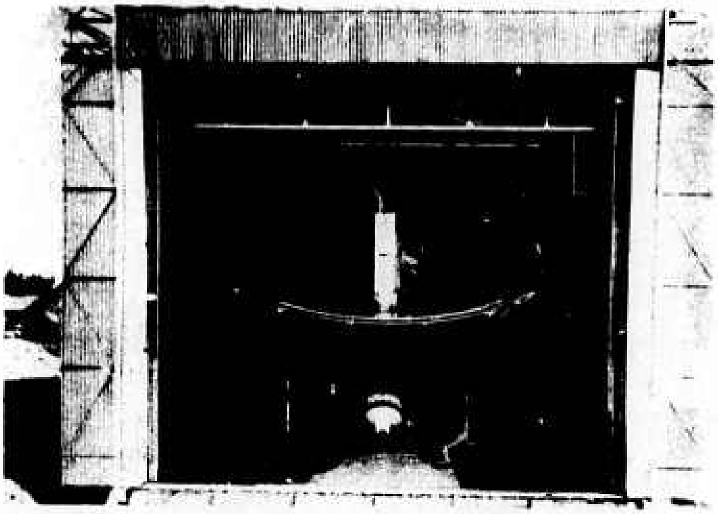

Fig. 52. Solar furnace at Bouzareah inside the hangar in bad weather [20].

## USSR

Using a solar furnace at Yerevan in the Armenian SSR, Soviet scientists have conducted a variety of tests with several refractory oxides and binary mixtures. These tests provided valuable data on temperature distribution, formation of the smelting zones, and the formation of crystals, as related to irradiation times. Microscopic studies of the phase composition of the materials indicate that these are crystals of a typical periclase* with perfect crystalline lattice [78].

Presently the Soviets are conducting research in plasma chemistry utilizing solar energy for determining the trend of chemical reactions, similar to investigations conducted in France and Japan. The State Institute of the Nitrogen Industry, Moscow has developed a small solar furnace for the photosynthesis of caprolactam. Parallel to this, scientists from the Institute of Physics of the Azerbaydzhan SSR Academy of Sciences, in conjunction with the Institute of Power Engineering, Moscow, recently conducted several tests on photosynthesis of caprolactam, plasma-chemical reactions, and other thermochemical investigations utilizing a small solar furnace (Fig. 53).

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* periclase- a cubic mineral, native magnesia ($MgO$) occurring usually in metamorphosed dolomite.

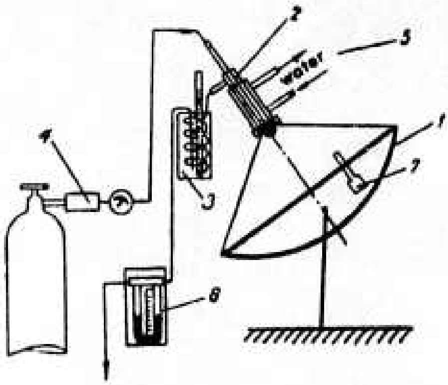


Fig. 53. Schematic of a solar furnace for thermochemical research, USSR [79].

1 - Concentrator; 2 - thermochemical reactor; 3 - tempering device; 4 - gas feed system; 5 - cooling system; 6 & 7 - not identified.

The concentrator uses a parabolic mirror 1.5 m in diameter, with a focal length of 0.637 m and an angular tracking range of 60-62° laterally. Mirror capacity was measured at 990 kcal/hr, or 1.15 kw equivalent, and a focused spot 11 mm in diameter produced 2000° C. Despite calculated losses (thermal conductivity and convection), temperatures of about 2500-3000° C have been obtained in the center of the focus; toward the periphery, the temperature drops to 1500-1800° C.

The principal component of the furnace is the thermochemical reactor (Fig. 54).

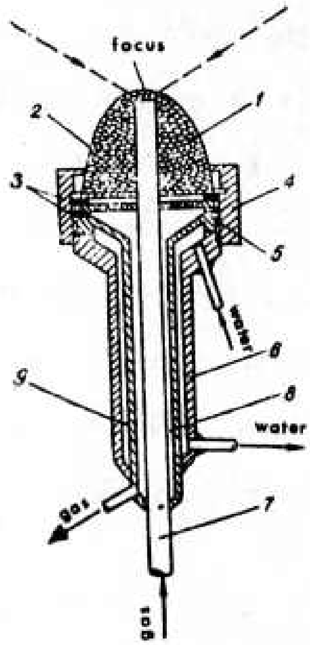


Fig. 54. Thermochemical reactor [79].
(Notations for 1-9 not given in original).

This particular solar furnace has been used to investigate the conversion of methane into acetylene, a highly studied subject in plasma chemistry requiring high temperatures for the dissociation of methane. The composite relation of gas-mixture balance during pyrolysis of methane, at a temperature of 1600° C, indicates that the maximum acetylene concentration reaches 25%. The computed compound balance of a complex system containing carbon and hydrogen indicates that, by increasing the mole fraction of the carbon in the mixture, the acetylene content increases. Therefore, it is desirable to fill the thermal cavity with poured or channel graphite, so that

sublimation of the graphite will take place in the focus at a temperature of 3500° C. Graphite is characterized by a high absorption coefficient, particularly important for a solar furnace [79].

By using graphite under atmospheric conditions, the maximum practical temperature that could be reached without causing too much sublimation would be about 3300° C. Besides graphite, the solid material having the highest known melting point is a solid solution of tantalum and hafnium carbide [19].

The Physicotechnical Institute of the Uzbek Academy of Sciences has designed a high-temperature vacuum-film solar furnace consisting of a domed vessel formed by inflating 1-mm-thick sheet aluminum with compressed air at a pressure of 2-3 atm, using a metallized polymer film prestretched on a frame in two directions. To obtain an air-tight seal, the film with its metallized side inward (this protects the aluminum layer against mechanical damage) is bonded to the rim of the vessel.

When a pressure difference is developed, the film assumes a shape close to a paraboloid of revolution. By varying the pressure, concentrating mirrors with a variety of focal lengths can be obtained.

In cited experiments, the diameter of the mirror surface of the solar furnace was 92 cm and the focal length was 120 cm, which corresponds to an aperture angle of $44^{\circ}$. This angle, determined by the deformation of the film in both directions, ensures maximum radiant flux density. The integral reflection coefficient of the mirror surface was determined calorimetrically, and its experimental average value was 0.86. Thermocouples placed at the focus of the furnace indicated temperatures of $950-1000^{\circ}$ C.

The focal spot of the furnace (1.8 cm in diameter) produced a radiant flux density in the solar image of about $1.7 \times 10^6$ kcal/$m^2$/hr, and a total radiant flux of 454 kcal/hr. The maximum attainable temperature for the above radiant flux density in the solar image is stated to be $2000^{\circ}$ C.

These experimental and computation data point to the possibilities offered by metallized polyethylene terephthalate film for manufacture of high-power solar furnaces [95].

Apart from other high-temperature sources, increasing use is now being made of solar furnaces that allow experiments to be conducted in a vacuum or some other controlled environment. In 1962, two such furnaces, 2 m and 1.5 m in diameter, were built by the Heliophysics Laboratory of the Physicotechnical Institute (Uzbek Academy of Sciences) to conduct research on the thermophysical properties of materials at high temperatures.

The furnace consists of a parabolic reflector with a mirror (2 m in diameter) and a heliostat with independent systems of azimuthal-vertical axes. The furnace can be used with direct orientation of the reflector toward the sun, or with the heliostat when the optical axis of the paraboloid is horizontal. The automatic electronic tracking system permits rapid adjustment of the heliostat and reflector. Accurate tracking during the daytime hours is accomplished by a sensor mounted on the reflector.

Total heat flux for the 2-m diameter furnace without the heliostat was measured at 1600 kcal/hr, and with the heliostat, at 1400 kcal/hr; for the 1.5-m-diameter furnace, heat flux was measured at 1000 kcal/hr. With these very large heat fluxes concentrated on the small area of the focal spot, heat flux density was estimated at $1 - 3 \times 10^6$ kcal/m$^2$/hr [92].

In discussing solar furnace techniques, Mavashev [93] notes that among various thermal regimes used in measuring the thermophysical properties of material at high temperatures, preference must be given to the thermal wave method. The thermal sine waves needed in this regime are generated by special devices that vary the heat load according to a sine law. In installations with resistance furnaces, the problem of generating sine waves is solved by the harmonic motion of the contact of the regulating rheostat. However, such systems are not suitable for investigating the thermophysical properties of materials in the 1000 - 1200° C range, owing to the technical difficulty of generating the required thermal waves. For research

on the thermal conductivity of metals at high temperatures by the thermal wave method, induction (from 700 to 1700° C), and electronic heating (from 1600 to 3000° C) methods have been used. However, the shortcoming of these methods is that they are useful for investigating the thermophysical properties of metals only.

The High Temperature Research Laboratory of the Physico-technical Institute (Uzbek Academy of Sciences) has developed a device for producing thermal sine waves utilizing solar energy applicable to the study of the thermophysical properties of materials at high temperatures. The heat source is a solar furnace 2 m in diameter, with a heliostat, permitting materials to be heated up to 3000-3500° C irrespective of their conductivity.

A periodical change of heat flux in the furnace is achieved by a modulating screen, a disk placed between the focus of the paraboloid and the paraboloid itself. The axis of the disk coincides with a principal optical axis of the parabolic reflector, and the plane of the disk is perpendicular to it. When the disk is moved along the optical axis of the mirror, the power of the light flux incident on the heated specimen changes. In order to vary the light flux according to a periodic law, disk is moved back and forth along the reflector axis by a cam mechanism driven by an electric motor (Fig. 58). The rpm and the oscillation frequency of the thermal waves are controlled by reduction gearing with interchangeable gears.

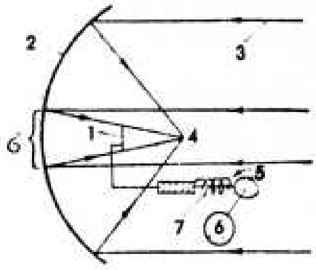


Fig. 55. Schematic of Soviet solar furnace with modulator [93].

1 - Modulating disk; 2 - paraboloidal mirror; 3 - sun's rays; 4 - focus of mirror; 5 - cam; 6 - electric motor; 7 - spring.

The device is equipped with a heat flux regulator in the form of a hollow cylinder. The axis of the cylinder coincides with the principal optic axis of the paraboloid. The constant component of the heat flux power is set by moving the regulator along the axis. The modulating disk (Fig. 56)

Fig. 56. Modulating disk [93].

is adjusted in relation to the position of the images of the disk itself and the regulating cylinder on the modulating screen, while the heat flux regulator is adjusted in relation to the illuminated ring on the cylinder (Fig. 57).

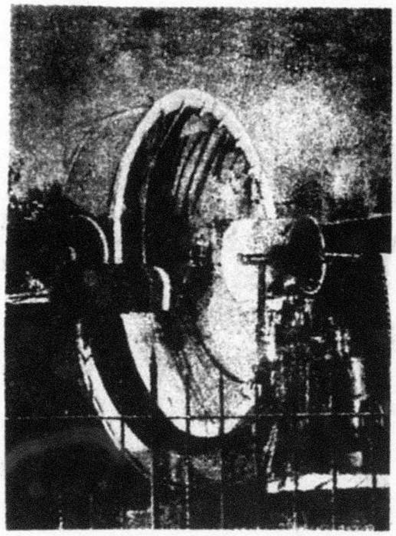



Fig. 57. Solar furnace and cylindrical heat flux regulator [93].

This solar furnace is used to measure the thermal conductivity of refractory and heat-resistant materials. Experiments can be carried out up to the melting point or destruction of the material being tested.

Experience has shown that high-temperature research is considerably facilitated through the creation of a stable thermal field, as well as by stable heat conditions in the receiver. Despite the fact that solar furnaces operate under conditions of continuously fluctuating solar radiation, the necessary receiver temperature regime (constant temperature at a certain

level, thermal shock, or programmed control) can be ensured by flux regulators that shade the collector (Fig. 58). Solar furnace regulators

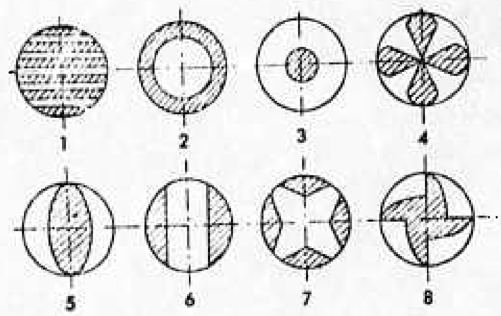


Fig. 58. Basic designs for collector shading [94].

may have a number of different designs for each of the diagrams shown. The simplest of these are illustrated in Fig. 59.

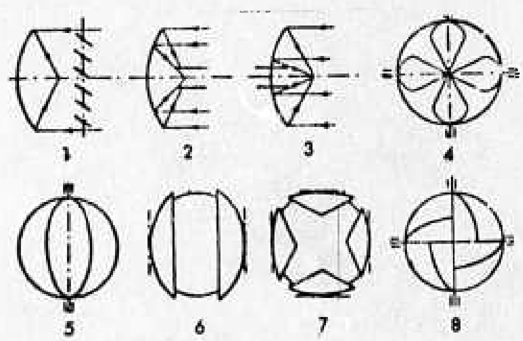


Fig. 59. Types of solar-furnace regulators, USSR [94].

1 - Louver type; 2 - cylindrical with screening of outer portion of the reflected flux; 3 - cylindrical, with screening of inner portion of the reflected flux; 4 - sectored; 5 - disk type, with rotating diameter; 6 - double-wing; 7 - lobed; 8 - sectored, with rotation of each sector about its radius.

Besides the shielding methods, one of the most practical methods of regulating the radiant flux in solar furnaces is to regulate the furnace power, since constant power regulation leads to a redistribution of the concentrated flux density in the focal plane [94]. For certain experiments, however, an instantaneous on-off control is necessary. Louver-type shutters are now in use on some furnaces which combine the effect of flux attenuation and on-off control. A disadvantage of this mechanism is that even in the fully open position it blocks some passage of radiation due to the thickness of the slats and support members [85].

Generally in the USSR, the construction of medium capacity solar furnaces up to 100 kw is undertaken by individual institutes. The construction of large solar furnaces is feasible only at the interdepartmental cooperation level. Regarding larger furnaces, the Department of Potential Power Sources of the Power Engineering Institute (Armenian Academy of Sciences) has conducted research and development with a large solar device, the BGUS concentrator, which has been successfully operating in Yerevan since 1963 (Fig. 60). The basic application of this unit has been in studying the effects of accelerated solar "aging" of materials.

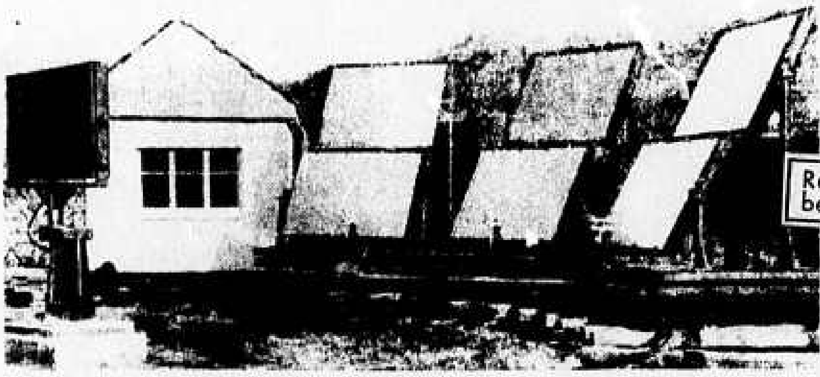



Fig. 60. General view of the BGUS solar installation, USSR [71].

This device consists of six plane reflectors composed of electropolished aluminum facets which concentrate solar rays onto a vertical

rack measuring 2 x 1 m. The reflectors, measuring 2 x 1.3 m, are mounted in pairs on three carriages which move automatically around a 7-m radius track. The rack on which test specimens are mounted is connected by a truss with hinged joints to the central driving carriage. The entire system revolves clockwise, from west to east, so that the test surface of the rack is always aligned with the reflectors. The device provides continuous automatic tracking of the sun by directing its optical axis in azimuth at the sun. This is accomplished by an automatic azimuth drive which has a sensor aimed directly at the sun and which actuates the drive carriage motor.

The elevation angle of the double reflectors on each carriage is controlled by an automatic electric drive which rotates the reflectors. The elevation rotation sensors on each carriage work off a reflected beam directed at the rack, maintaining a constant target elevation.

The six azimuth-elevation rotation sensors of the reflectors, controlled by the reflected beam, have cylindrical collimation tubes mounted in pairs on a common counterbalanced bracket having two degrees of freedom of rotation. The sensors, always correctly aimed at the rack, are mounted on the frame of the corresponding carriage. A seventh azimuth motion sensor, operating directly off the sun, has a collimator in the form of a segment with a vertical entrance slit; it is attached to the truss connecting the rack with the center carriage. For rapid adjustment of the components, besides automatic control, the device is provided with manual control.

The basic reflector requirements for an accelerated solar aging testing device are retention of the total solar spectrum, good reflectivity, and weathering resistance. Retention of the ultraviolet portion of the solar spectrum, a major factor in the aging of materials, represents the greatest difficulty. Various investigations show that electropolished aluminum has a relatively constant and sufficiently high reflection coefficient, averaging 75-80%, including the ultraviolet region. The high wear resistance of industrially produced electropolished aluminum sheet, its high resistance to weathering and very gradual degradation (6-8 years), demonstrate its suitability for reflector material.

It is evident that to analyze the aging test results, the amount of radiation incident on the rack should be known as well as its variations with time. These data are obtained by pyronometric measurement of the total radiation from each of the six reflectors individually at 36 equidistant check points.

Results of accelerated aging tests of polymer materials on the BGUS show the great advantages of the new testing method. The aging process occurs under conditions close to natural, but, through multiple intensification of solar radiation, the period of natural aging is accelerated by a factor of 5 - 10 depending upon the type of material being investigated.

Solar aging devices of this type can be widely used not only in testing insulating and protective materials in the electrical engineering industry, but also in the construction, chemical, and light industries. In addition, such solar devices could play a major role in the development and inspection of high-quality products intended for operation under tropical conditions [71].

In 1972, the Physicotechnical Institute of the Uzbek Academy of Sciences conducted research on the "Sirius" solar furnace. This furnace has biparabolic mirrors 1.5 m in diameter, direct tracking, and a capacity of 45 and 100 kw equivalent [26].

The Moscow Institute of Power Engineering designed and is experimenting with a combined solar arc optical furnace for high temperature research (Fig. 61 & 62).

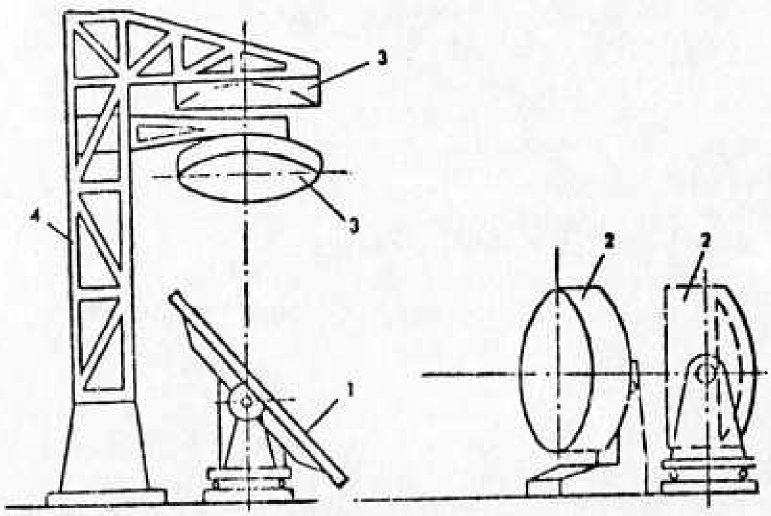


Fig. 61. Side view of the solar arc optical furnace, USSR [36, 89].

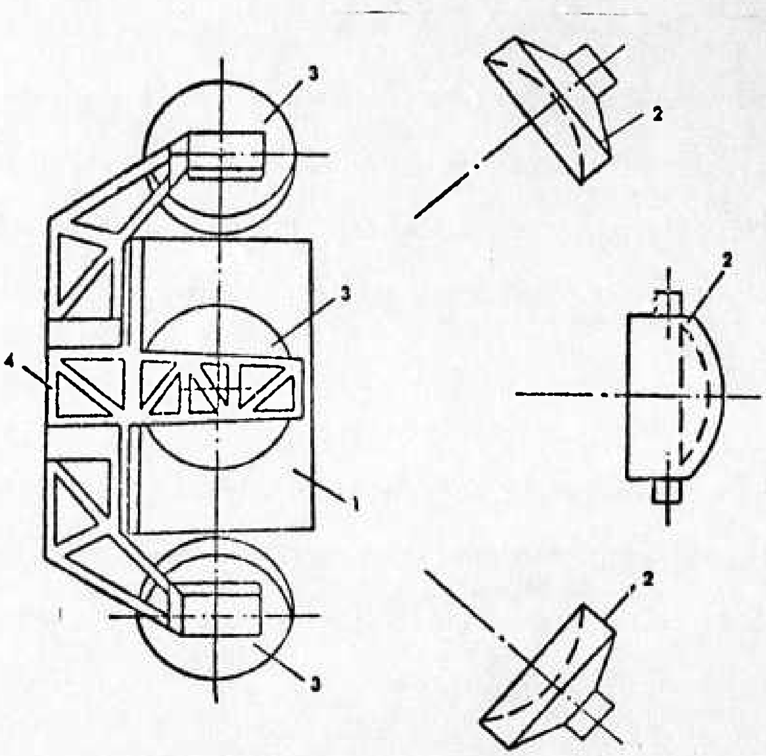


Fig. 62. Plan view of the solar arc optical furnace [36, 89].

1 - Heliostat; 2 - paraboloidal concentrators with horizontal axis; 3 - paraboloidal concentrators with vertical axis; 4 - support.

This unique unit produces high thermal fluxes, using either solar energy or the radiant energy from an electric arc or powerful electric lamp positioned in the focus of one of the concentrators.

The unusual feature of this device is a flat strainable heliostat that receives direct radiation which can be switched from one concentrator to another. The optical axes of the concentrators, which can

be fixed or movable, are arranged in horizontal and vertical planes and are trained on the center of the heliostat.

All the concentrators are equipped with photoelectric tracking sensors. Each concentrator tracking system is individually connected to the heliostat drive unit which is controlled by a switching system in the control panel. The heliostat tracking drive receives signals from a concentrator's sensor system and automatically maintains the desired position. The sensor systems of the other concentrators are not active until switched on at the control panel [89].

Test samples can be positioned in the focus of one or all the concentrators. When one test is completed, the sun tracking system receives a signal from the second concentrator, the heliostat repositions itself, and the second test begins. The cycle repeats until all the tests are completed.

This new furnace differs from others by its increased testing capacity, the ability to transmit radiant energy in different directions to vertically and horizontally aligned concentrators, and by ensuring continuous testing operations in any weather and at any time, using an alternate artificial source of intensive radiation [36].

An experimental solar furnace (Fig. 63) with combined

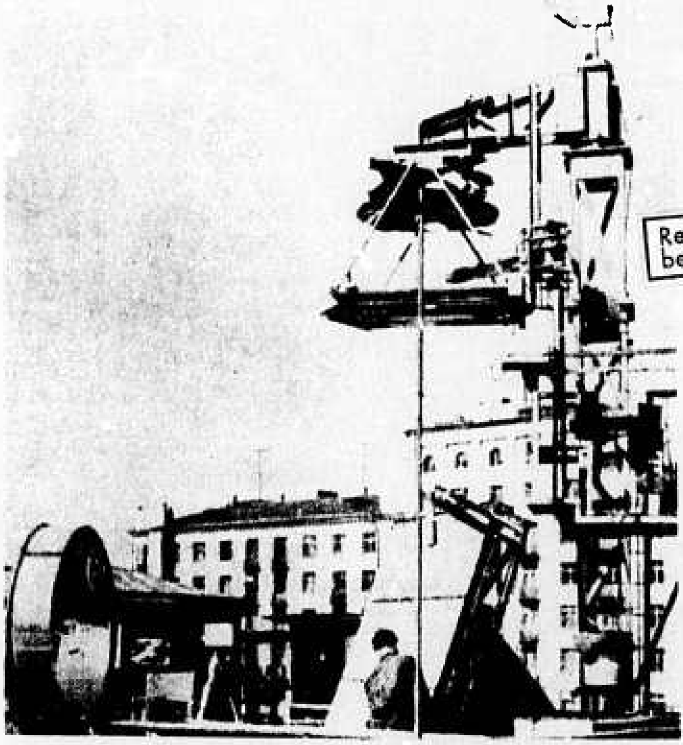



Fig. 63. General view of the solar furnace and the rig [91].

double-mirror concentrators was designed by the Moscow Institute of Power Engineering, for general and specific applied high-temperature solar-energy converters, and for studying the thermophysical and technical properties of materials at high temperatures both in various atmospheric environments and in a vacuum.

This solar furnace has two fixed paraboloidal searchlight reflectors with nominal diameters of 1.5 and 1.2 m and focal lengths of 639 and 630 mm, respectively.

The large mirror has a horizontal optical axis, with a 115 mm hole in the center used for centering the specimen, observing the process, and measuring the temperature in the specimen.

The optical axis of the smaller mirror, suspended from a cantilever mount extending out from a 4.5-m-high welded column, is aligned vertically. The cantilever mount can be turned about its vertical axis, if necessary. During experiments, the upper mirror is serviced from a special stage also attached to the column. This arrangement of the paraboloidal reflectors permits experiments to be conducted with irradiation from the side and from above. The latter orientation is mandatory in certain studies of molten materials.

The rectangular heliostat (2.8 x 2.1 m) is designed so that the two concentrators operate independently. The heliostat consists of 12 square polished mirrors, 10-mm thick, mounted on a single flat frame. When serving the upper or lower concentrator, the heliostat moves in conjunction with the apparent motion of the sun driven by an azimuth and elevation tracking system. The drive mechanism consists of motors with azimuth and elevation reduction gears.

The lower mirror has a cylinder-type control system with a photoelectric pyrometer as a sensor. The upper mirror is equipped with a sliding shade mounted in the flux reflected from the heliostat; its sensor is a standard pyrometer attached to the shade, with its sensing element facing the heliostat. The radiant flux is directed onto the pyrometer from below, and is measured by a special disk chopper kinematically connected to the main shade control. The different control principles on which the systems are based enable researchers to vary the character of the change in irradiation parameters on specimens mounted in the focus of each mirror [91].

A similar double-mirror experimental solar furnace is in service at the Institute of Electronics of the Uzbek Academy of Sciences, the major difference being that the mirrors are 1.5 and 2 m in diameter.

At the Armenian Base Laboratory of the All-Union Scientific Institute of Fuel Utilization (VNIIT) at Yerevan, an experimental high-temperature solar furnace has been installed with vertical optical axis and a paraboloid 2 m in diameter. This 2-meter solar furnace is used for growing artificial single crystals and for melting or refining refractory metals and alloys. The installation consists of a 4-story structure (Fig. 64) attached to the southern side of the main laboratory building.

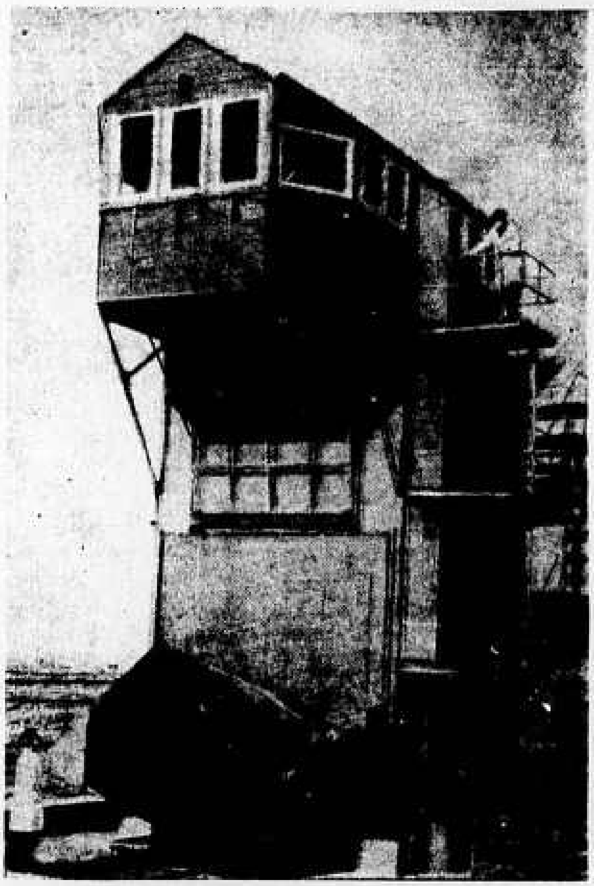

Fig. 64. General view of the high temperature solar furnace in Yerevan [88].

A rail-mounted heliostat, 2.9 x 3 m, is located at ground level and is equipped with an automatic sun tracking system.

The fourth floor houses a parabolic concentrator (Fig. 65) at a height of 9 meters in an enclosed overhang. The concentrator room is used for all experiments and the monitoring of process operations. A retractable glass floor under the concentrator permits work at room temperature during winter. The heliostat has a double drive system, i.e.,

electromechanical and hydraulic, and operates at an inclination of 15°
to the vertical optical axis. In addition, it is equipped with automatically regulated louvers and an iris diaphragm.

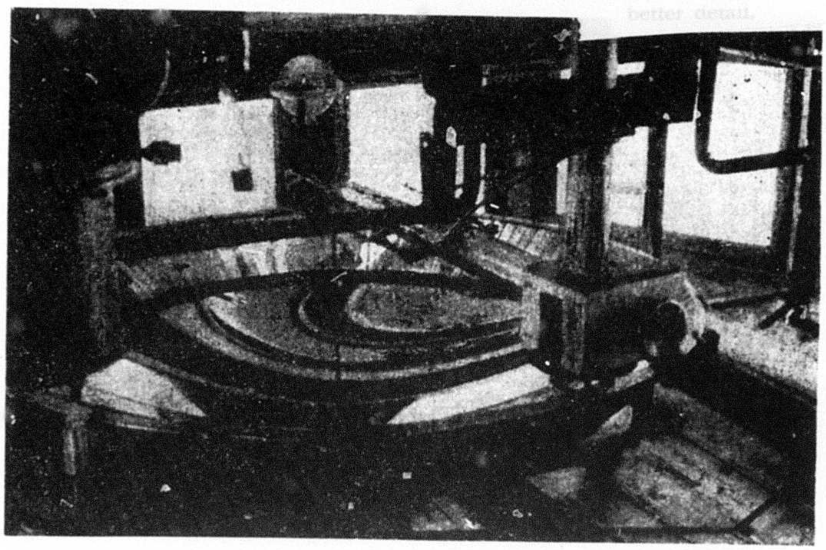

Fig. 65. Interior of high temperature solar furnace operating room [88].

Based on experience with above experimental furnace, as reported in a 1969 source [88], in 1970 this same laboratory was to have started construction of a solar furnace with a 10-m diameter concentrator which will have vertical and inclined optical axes, the latter used to achieve direct tracking of the sun (Fig. 66).

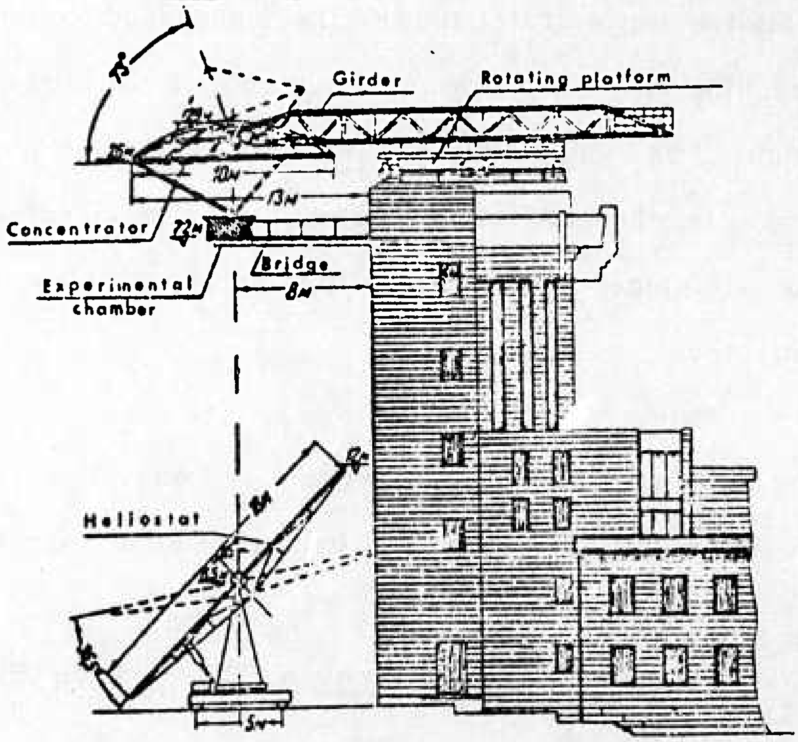


Fig. 66. Design of a Soviet solar furnace with a 10 m concentrator. (dimensions in m) [88].

This design will use a heliostat when the concentrator is in a down vertical or depressed position, while a direct sun tracking capability will be available by rotating the concentrator through 163° to a maximum elevation of 73°.

On top of the supporting structure is a rotating platform with the 10-m diameter parabolic concentrator suspended from a cantilevered girder.

Galvanoplastic mold-copying technology will be used to fabricate the concentrator from a mold produced by centrifugal casting. For tracking the sun, a special drive rotates the concentrator to an elevation maximum of 73° and simultaneously turns the rotating platform about its vertical axis, thus providing tracking. During direct sun tracking the test sample is fastened in a special tripod holder attached to the rim of the concentrator.

At the Moscow Institute of Power Engineering, there are proposals for the construction of two large solar furnaces described as follows:

o <u>SP-25 solar furnace</u> This furnace (Fig. 67) will have a

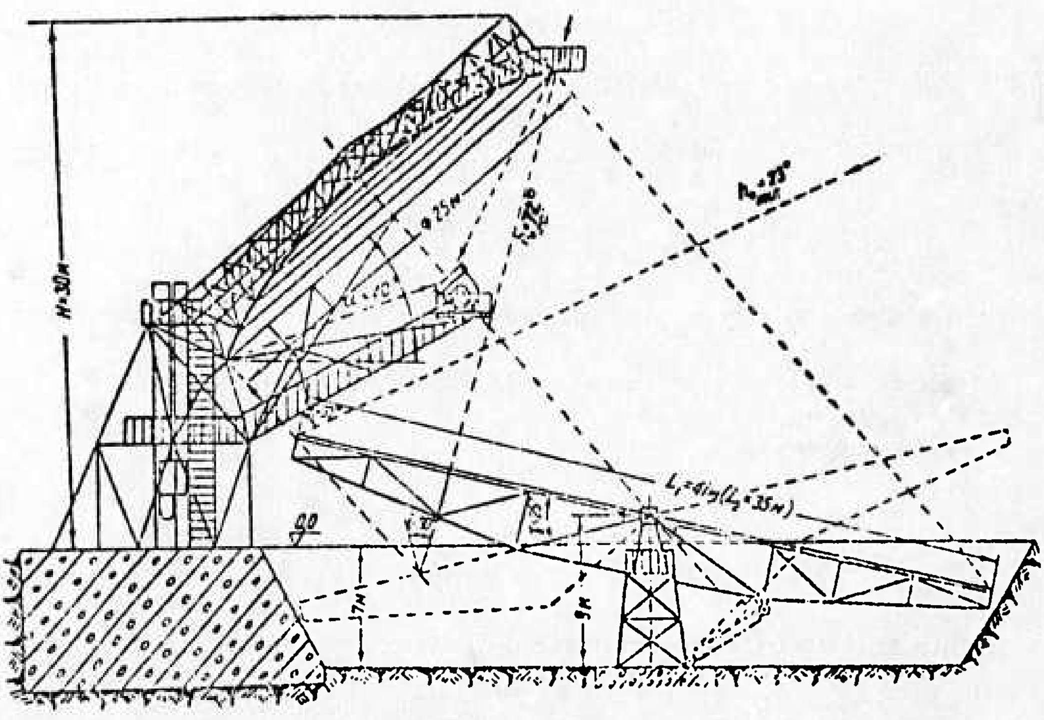

Fig. 67. Planned SP-25 solar furnace, USSR. (dimensions in m) [88].

plane mirror heliostat (35 x 41 m) and a parabolic mirror concentrator 25 m in diameter with a 9 m focal length. The concentrator will be mounted on a stationary metal- and reinforced concrete structure, inclined at an optimal angle depending on the geographical latitude of the site. The heliostat is positioned in a pit, which will reduce the total height of the structure and simplify the overall arrangement and operation of the furnace. The heliostat will have a hydraulic drive, controlled by signals from the tracking system.

The optical arrangement permits testing of diverse specimens with irradiation from various positions. The capacity of the furnace is estimated at 250 kw, the diameter of the test zone is 360 mm, and a maximum temperature of 3200° K is expected.

o SP-32 solar furnace. This furnace (Fig. 68) will have

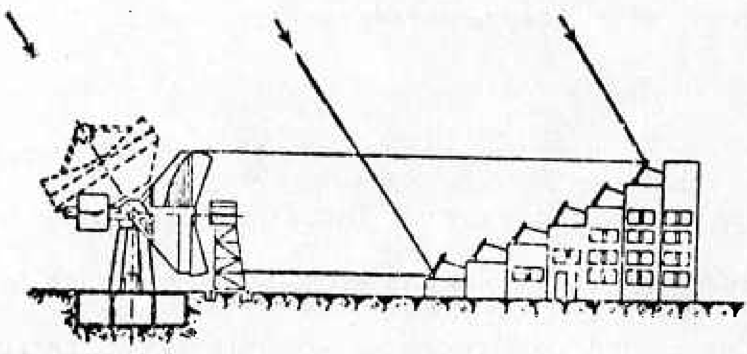

Fig. 68. Planned SP-32 solar furnace, USSR [88].

a paraboloid 32 m in diameter and an 11 m focal length. The large framework supporting the parabolic mirror components will be installed on a reinforced concrete turret and can train to azimuthal-zenithal bearings. If the optical axis of the paraboloid is horizontal and aimed toward the north, it will receive direct solar radiation from 40 heliostats, 6 x 8 m each, mounted on the terraced roof of a public building. Each heliostat is equipped with hydraulic drive and is controlled by a master tracking system. The sample testing unit used with the concentrator is installed on a separate tower which can be moved away from the paraboloid on rails. In the tower, test support systems such as the vacuum system, various types of louvers, screens, and shutters for controlling radiant flux, etc., are mounted. When used with direct tracking, the sample testing unit can be mounted on the paraboloid.

The capacity of this furnace is estimated at 320 kw, using the heliostats and with radiation at 814 watt/$m^2$; with direct tracking on the sun this rises to 400 kw. The diameters of the test areas are to be 450 and 240 mm, with maximum temperatures of 3200 and 4600$^\circ$ K [88].

In general, experience to date has shown that the potential application of solar furnaces to industrial processes requiring high temperatures under controlled conditions has stimulated research in the fields of solar furnace design and construction, development of instruments, experimental investigations and process development.

The development of new reflecting surfaces and supporting structures opens up the possibility of constructing large solar furnaces at more reasonable costs. Although for large solar furnaces the efficiency of utilizing solar energy may not be the prime concern, every effort should be made to obtain the greatest possible efficiency. The geometrical perfection of the reflector and the effects of oxidation and erosion of the reflecting surface must be taken into account. The utilization of all available heat flux requires that the material or process be arranged to limit the losses from heated surfaces due to reflection and to reemission from surfaces not receiving radiation. Cavity heating and effective thermal insulation can greatly reduce unwanted heat losses. Accurate sun tracking has been developed so that no loss in efficiency need result, and the optical axis of the reflector can be kept continually parallel to the rays of the sun.

The development of instruments for measuring temperature and heat flux have greatly aided the experimental investigations in which solar furnaces are used. Temperature measuring instruments, using shutters to separate the radiation emitted by the sample from the radiation reflected from the surface of the sample, permit the use of optical pyrometers. Absolute water-cooled calorimeters for measuring the total heat flux and radiometers for measuring the flux distribution across the sample area allow the heat flux reaching the sample to be controlled. Cylindrical shutters and louver-type shutters have been used to control the quantity of radiant energy reaching the sample. A flux redistributor has also been developed

which collects the energy at the focal zone of the solar furnace and redistributes it over a larger area. The development of advanced designs for constructing large solar furnaces, the availability of instrumentation and the results of numerous experiments are setting the stage for the industrial uses of solar furnaces. Some of these industrial uses have already become reality, e.g., the treatment of batches of refractory materials to achieve higher levels of purification.

As the cost of reflectors and auxiliary equipment is further reduced, industry will become increasingly interested in applying solar furnaces. Current investigations which are aimed at achieving a better understanding of the requirements for furnace construction, temperature generation and control, instrumentation and component design should indicate the most promising applications [86].

B. Water Heating

It has been computed that the roof of an average home receives about 100 times as much energy from the sun as could be used inside for lighting, cooking, heating, air conditioning, heating water, etc. [63]. As one example of using this energy, let us consider water heating.

Solar water heating is the only commercially available application now competitive with other water heating methods in many parts of the world. In southern Florida, the solar water heater is almost a standard piece of domestic equipment, with about one dozen solar water heater manufacturers in this state alone. In Japan, solar water heaters are produced at a rate of 100,000 annually. In Northern Africa and Israel the number of water heaters has recently increased considerably. Swimming pool heaters, generally of the same design as the solar water heater, have become quite popular in the United States, extending the swimming season considerably, from 50 days to about 150 in the north [3]. Australia, with its rapidly rising population and its relatively high energy cost, is witnessing a major increase in the number of solar water heaters currently in use [38].

The popularity of solar water heaters, which can suitably be used in areas between latitudes 45° North and South having more than 2,000 hours of sunshine per year, and which achieve temperatures up to

about 70$^\circ$ C, may be traced to the growing demand for hot water, the simplicity and the usually low cost of equipment, and an improved competitive position in relation to other sources of heating.

In its simplest form, a water heater consists of a plastic "pillow" containing 200 liters of water; it has no separate storage unit and is tapped in the afternoon or evening for bathing and other uses. An insulated box with a transparent cover, regulated by hand, operates in the same way.

Most types, however, have a separate storage unit to provide hot water at any time. They typically consist of a blackened metal absorber surface, containing ducts to let water through for heating, in an insulated box with a transparent cover (to reduce heat losses), an insulated storage tank, and piping for water to the absorber, the tank and the point of use. The hot water usually rises in the tank by natural (thermosiphon) circulation so that no mechanism is needed, but a small pump may be added to force the circulation or change its direction. There are many variations in these basic elements, such as in the choice of materials for the absorber and other parts, the arrangement of ducts in the absorber, and the orientation and inclination of the unit in relation to the incoming solar energy. Among recent innovations are the use of plastic coating to prevent corrosion, plastic tubes in the water ducts to avoid freezing, the introduction of flexible inclination (allowing seasonal change with solar altitude to increase efficiency), and an irreversible thermosiphon.

Some absorbers have copper plates with copper tubes soldered into them; others consist of two flate plates riveted, crimped, or welded together. The most efficient unit found consists of two thin flat copper sheets fastened at the edges, which provides a water space of about 1/4 inch with one glass cover and 1 inch of styrofoam insulation behind the plates. (No plastic materials have been found to be as good as glass, since none of those tested transmitted short waves while trapping the long wave radiation. This characteristic of glass is well suited to the design of solar traps).

The typical Florida solar water heater consists of a sheet metal box, 4 ft by 12 ft, covered with a layer of glass. Inside the box is a copper sheet with copper tubes soldered to it in a sinusoidal configuration and connected to an 80 gallon water storage tank. Under the copper sheet is one inch of styrofoam insulation. For satisfactory operation, the bottom of the hot water storage tank must be above the top of the absorber in order to provide circulation without a pump.

The standard units may be damaged if used in freezing temperatures, so a dual circulation system which eliminates the problem has been developed. It consists of two tanks, one inside the other, the outer tank being connected to the collector. This system is filled with an anti-freeze solution. The heat is then transferred from this solution through the wall of the inner tank to the water to be used. Since in this system the

primary circuit operates at atmospheric conditions (the outer tank need have only a lid on it), the collector can be constructed much less expensively with less weight; insulation covers the outside tank. A system of this type satisfactorily serves a typical American family of four with an automatic washing machine, etc. [47].

Another type of heater of interest to many people in Florida and California is a swimming pool heater. This is one of the simplest and least expensive heating devices. It consists of a galvanized sheet wrapped in plastic, the sheet being coated with a good absorbing paint. Water from the pool can be fed to these absorbers by the filter pump and then, running down both the front and back of the metal plate, drain into the pool. It usually takes a collecting surface equal to the pool surface to raise the water temperature in the pool $2^{\circ}$ F. These absorbers can be constructed to form the fence around the pool, which in many localities is required by law and which provides privacy [47].

Every solar hot water system must absorb energy from the sun, transmit it to water and then store the hot water until it is needed. The method of doing this divides the systems into three groups:

- o Absorbing and storing in the same unit;
- o Absorbing and storing in separate units;
- o The dual circulation system

Systems of the second type with an absorber which collects the sunshine and a separate, well-insulated storage tank, are the most common. The water flows by natural convection between absorber and tank if the tank is located higher than the absorber, or else is circulated by means of a small pump for other arrangements.

The designs of absorber units which are currently used in different parts of the world can be put into five classes as follows:

Pan-type. Fig. 69 shows the water-filled pan design. The

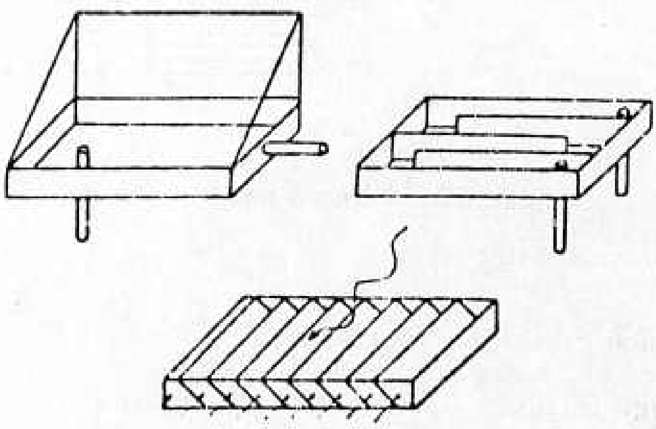

Fig. 69. Pan type solar absorbers [63].

pan is coated with a good absorbing paint which after converting the absorbed energy into heat delivers it to the water. The water is often stored in this pan until needed, or sometimes flows slowly through the pan and then into a storage tank. In the latter case, divider strips are often

placed in the pan to give a definite flow path. The pan can be covered by a horizontal or inclined glass sheet. These units are found, for example, in the rural areas of Japan.

A Russian design uses glass for the divider strips and by inclining them perpendicularly to the sun effectively a double glass cover is obtained [63]. This is more efficient but also more expensive.

Sinusoidal tube type (Fig. 70) in its simplest form consists

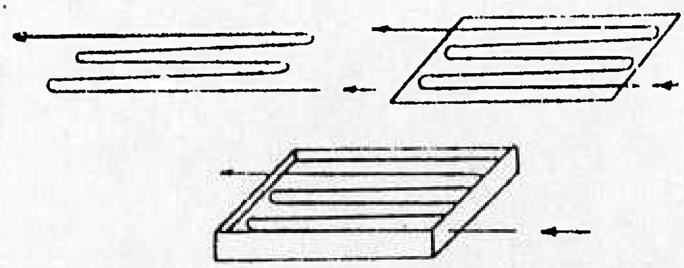

Fig. 70. Sinusoidal tube type solar absorbers [63].

of a long tube coiled back and forth to conserve space which absorbs the solar energy falling upon it and heats the water inside. Only with much sunshine is such a crude system satisfactory; in most areas it is necessary to put the tube on a metal sheet and in a "hot box" - a box insulated against heat losses and covered with glass. An alternative is to imbed the tube in a slab of concrete which is exposed to the sun.

Tubes placed on the roof in some cases have performed satisfactorily in South America and Spain. Most of the installations in the United States are of the sinusoidal type using copper tubing soldered to a thin copper sheet. The copper sheet conducts all the energy falling upon it to the pipes or tubes, thus intercepting and utilizing a much larger amount of energy.

Straight tubes and ducts with headers (Fig. 71) or round or oval tubes, closely spaced, are connected by two headers. The tubes can be horizontal or inclined. Oval tubes facing the sun with their broader side have the advantage of containing less water for a fixed area of solar radiation and will therefore deliver hot water sooner after exposure to sun. This time lag can be reduced further by using rectangular ducts which contain only a thin layer of water. Arrangements of this type can be found in the U.S.S.R. and Israel.

The Japanese sometimes use simple ladder arrangements of pipe or tube on roofs, performing satisfactorily there. In the U.S.S.R. a similar system is put on top of a corrugated metal sheet, which increases the effectiveness of the system. The performance is further improved by putting this arrangement into a "hot box" [63].

The relatively new development of fabricating tubes directly in the sheet (tube-in-strip), and then hydraulically expanding the tubes also belongs in this category. It is less expensive than having the tube fastened to a sheet and gives better contact and thus better heat transfer between the sheet and the tube.

Generally every inclined collector will have cold water flowing in at the bottom and hot water out at the top. Since the water-to-absorber-tube temperature difference is greater at the inlet, the lower part of the absorber is more effective than the upper part. Dividing a large absorber into a number of small ones, all in the same "hot box," and feeding all the small absorbers from a tube at the bottom and extracting the hot water through tubes at the top is more effective; up to 81 percent efficiency has been reported in this design.

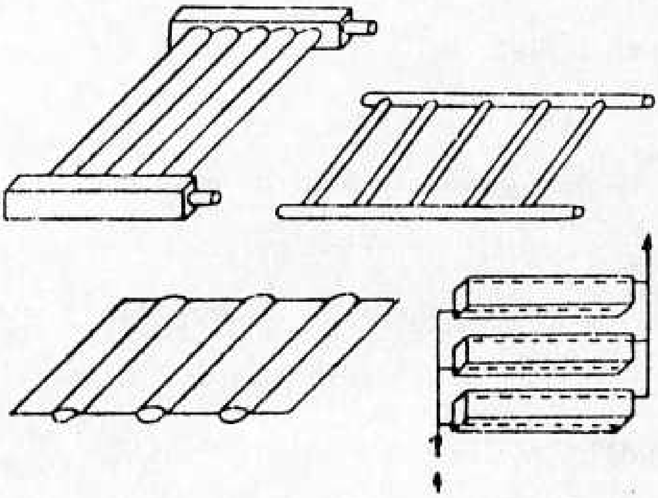

Fig. 71. Straight tubes and ducts with header-type solar absorbers [63].

Flat-plate type (Fig. 72). This absorber consists in its

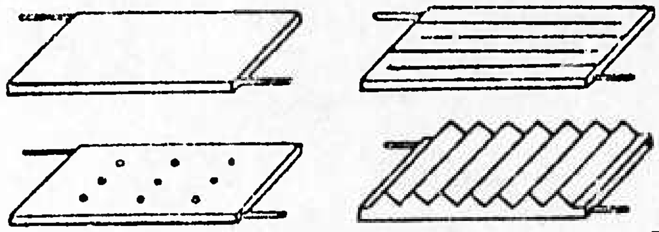

Fig. 72. Flat-plate type solar absorbers [63].

simplest form of two flat plates or thin metal sheets fastened at the edges. If water flows between the plates, this design gives all the advantages of the straight-tube closely spaced unit, but is less expensive. If this absorber is to operate under pressure, then spacers, rivets or strips must be used for strengthening. In Japan, for strengthening, the upper plate is ribbed. The simple flat-plate collector is ideal for use with a low-pressure system, or as part of the primary circuit of the dual circulation system described below.

Kawai solar water heater. This Japanese absorber heats the water while it slowly flows from top to bottom through a fabric between two metal plates which are placed in a "hot box". Frost will not damage this unit (Fig. 73).

For free circulation, it is necessary that the water storage tank be higher than the absorber. Since the absorber is often located on the roof, the tank is frequently concealed in an attic, in a false chimney, etc.

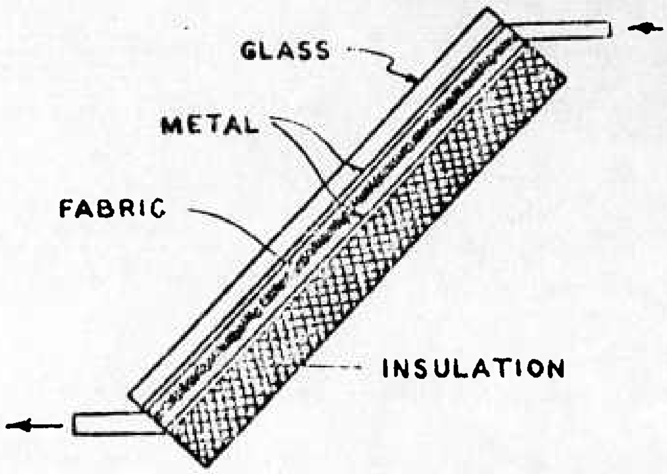


Fig. 73. Kawai solar absorber [63].

In Israel, a solar circulating pump is used to some extent so that it is not necessary to have the tank higher than the absorber. The same can be done by installing a small electric circulating pump.

Glass covers on the solar absorber transmit a considerable portion of the short wave radiation from the sun but reflect some, especially at the small angles between sun ray and glass. The long wave radiation from the hot surfaces of the absorber is transmitted only to a small degree. Glass with high iron content (greenish tint on the breaking edge) should be avoided. Experiments underway with better paints and coatings and with plastics instead of glass promise both to increase performance and decrease the cost. The construction materials determine the amount of maintenance required, which should, however, in all cases be low; there are units which have been in operation for almost forty years with minimal attention [63].

The amount of solar energy transmitted depends greatly upon the angle at which the sun rays hit the glass, which varies continuously all day. When more than one glass plate is used, the amount of energy transmitted is further reduced, but at the same time the heat losses from the top of the absorber box are reduced since the air layer between the glass plates has good insulating qualities.

The most common fault of solar hot water installations is inadequate storage. If the hot water stored is used up during the night, no more can be obtained until the sun shines again. If the tank is too small, then once the water is hot, circulation between the absorber and tank will stop and the system becomes inoperative even with the sun shining until some of the hot water is used.

Whether solar water heating is economical and advantageous in a given case will depend on many factors, the most important being the amount of available sunshine, availability and cost of the fossil fuels, cost and design of solar water heater installations, and duty cycle of the solar water heater system [63].

A new type of solar water heater has been developed and tested in the U.S. which combines sheet metal with durable plastic tubing [108]. The metal sheet is corrugated in a special way, forming tubular openings, into which plastic pipe is inserted forming a continuous coil. The inherently

heat conductivity of the plastic is increased by incorporating metal powder into it before extrusion into tubing.

The new design and its performance shows the advantage of an all-metal panel: it is not damaged by below-freezing temperatures nor by heat (when heat resistant plastic tubing is used); it is lighter in weight and easier to install, is less expensive, and it is leakproof as the need for soldered or welded pipe connections is eliminated. There panels can be employed for many applications in the heating and cooling fields; for example two swimming pools have been equipped with solar heaters made of panels following this design. Test results indicate that pool temperatures in excess of 70° F could be maintained during 152 days, while the usual swimming season is limited to an average of 50 days, e.g., in Princeton, New Jersey (latitude 40°) on the east coast of the United States. Cooling is obtained by circulating water from the pool through the panels during the night. Tests made during the month of June showed that a cooling effect of 500 btu/sq.ft. could be obtained during clear nights [108].

Algeria

With this brief background we will now further examine some foreign technology in solar heaters. The University of Algiers, has designed and tested economical solar water heaters for the undeveloped regions of Algeria [109]. The first type is small (70 cm in its largest dimension) and provides a limited amount of water. This model has a single glass pane 50 x 70 cm in front. The flat heating tank has the same surface

area and a wall thickness of 45 mm, giving a capacity of about 15 liters. The glazed box is 56 x 75 x 11 cm overall, supported by three legs; the rear leg is adjustable. The complete heater weighs 21 kg, (Fig. 74).

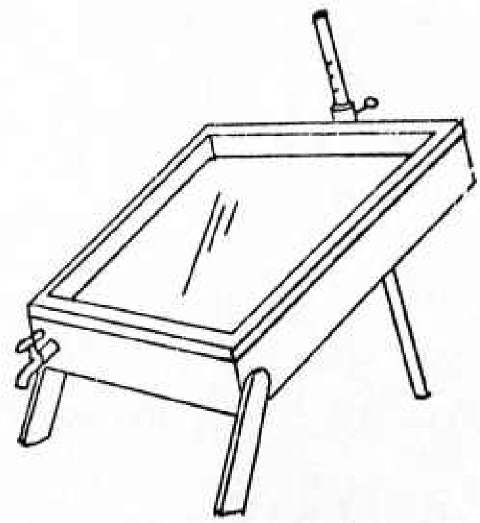

Fig. 74. Small solar water heater, Algeria [109].

A second larger model is mounted on a frame with four glass panes, each 40 x 60 cm. The insulated surface is 9600 $cm^2$, the water volume 50 liters and the glazed box is 92 x 133 x 20 cm overall. The total weight of this heater is 72 kg, empty (Fig. 75).

The ratio of exposed area to volume of water heated is 48 $l/m^2$ for the small model, and 52 $l/m^2$ for the large.

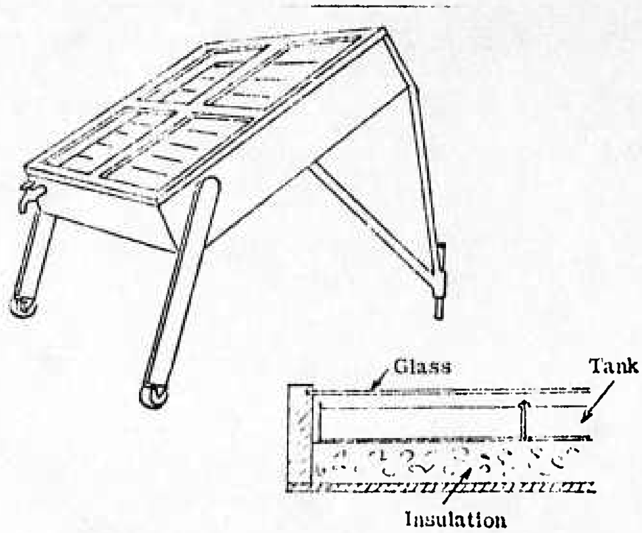


Fig. 75. Large solar water heater, Algeria [109].

The water is heated gradually, beginning in the morning. Its temperature rises at first in the upper part of the tank, gradually reaching its maximum from 3 -- 5 p.m., according to the season, and then slowly declines. There is a constant vertical gradient of water temperature since the water is naturally at the lowest temperature near the base. The water is withdrawn for use at a level about quarter of the way up.

These heaters consist essentially of a flat chest with bottom and sides insulated either by wood shavings between two sheets of isoral (small model) or by cork panels between two thicknesses of boards (large model). The shallow metal water tank with blackened face is placed in this

chest. The chest is closed by a glazed frame that transmits sunlight. It is supported on three feet, two in front and one in back, and is inclined so that the incidence of sunlight is normal at the time of the equinoxes; the angle of inclination may vary by adjusting the rear foot, which consists of a tube sliding in a casing.

The storage tank in the large model is made of commercial corrugated galvanized iron. The corrugations are spaced 75 mm apart, with depth of 18 mm between crest and trough. The corrugations impart additional rigidity to the walls, which tend to deform under the action of the temperature rise. Four threaded rods with nuts maintain the distance between walls in the central and lower portions. The metal sheets are welded at their ends to a flat galvanized iron wall, and are arranged so that the troughs of the corrugation of one wall are directly opposite those of the other. The storage tank in the small model is made of sheet zinc and the separation in this case is also maintained by cross pieces [109].

## Australia

Water heating in Australia is a major fuel consumer and in this respect, solar energy could make a valuable national contribution, but it most compete on economic grounds. The key to this is a cheap absorber. It is suggested that the objective ought to be an absorber which would recover its capital cost in three years, and must be very cheap and easy to install.

Materials such as copper seem to be out of the question; other metals such as galvanized iron or even black iron are possibilities, but it is doubtful whether they would have sufficient life under operating conditions. Plastics seem to offer the most attractive possibilities, particularly the polyvinyl fluorides which appear to have the necessary durability under both solar radiation and high temperature.

In developing these cheap absorbers, efficiency will be unimportant provided the above requirements are met. Extreme simplicity of installation is necessary to reduce expensive plumbing to an absolute minimum.

Concentrating devices have been used in Australia for water heating with flat plate absorbers operating at a high collection efficiency, and are inherently simpler, easier to install, and require less maintenance than collectors using parabolic or other types of reflectors. It is only the flat-plate absorber which is now in commercial production throughout Australia [64].

When this design was first introduced, there seemed no prospect of finding materials even with a short life which would enable a design to be developed whose cost could be recovered in, say, three years. Accordingly, it was decided to aim for a life in excess of 25 years, the cost of which could be recovered in less than 20 years. The basic materials

chosen were asbestos cement sheet for the case, glass covers, and a copper absorber plate with mineral wool for the rear insulation.

Edge losses will obviously be proportionately reduced the larger the unit becomes. There is also considerable advantage in selecting a design in which the glass is held only at its outside edges. The largest sheet which could be supported in this way without using heavy and expensive glass is about 4 ft, which led to the choice of a nominal 16 sq ft absorber. The asbestos cement absorber case is molded in one piece with an internal ledge to support the inner glass and another ledge to support the absorber plate. The outer glass, which has to withstand weather conditions, is 32 oz/sq.ft., while the inner glass is 26 oz/sq.ft. (Fig. 76).

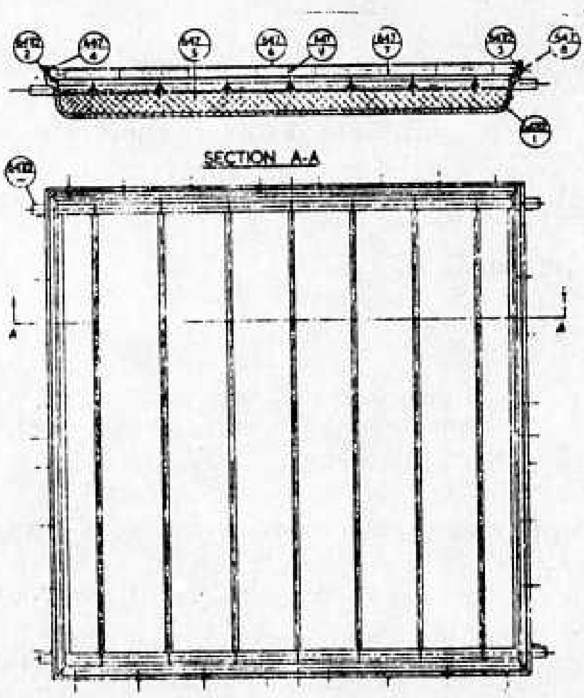


Fig. 76. General arrangement of absorber with asbestos cement base, glass cover sheet and copper absorber plate, Australia [64].

The choice of the optimum number of glass cover sheets and the extent to which the rear and edges should be insulated is a more complex problem. It has been suggested that the thickness of the edge insulation should equal that of the rear insulation, based on optimizing the design from the point of view of losses. However, for a given size of external case the edge insulation reduces the area of plate which can be exposed to radiation, and under certain circumstances it can be shown that the increased energy absorbed is more than the extra losses which would take place if the insulation were not present.

Since under operating conditions water is heated daily from mains temperature up to the operating temperature of $135^{\circ}$ F, the effective temperature characteristic of the daily losses will be a weighted mean. For a water inlet temperature of $60^{\circ}$ F this has been found to be $105^{\circ}$ F; thus if we assume that the ambient temperature is not substantially different from the water inlet temperature, the mean temperature difference between the plate and ambient is $45^{\circ}$ F.

A common practice which has been followed for a number of years in Australia is to provide 1 1/2-2 days supply in an insulated storage tank. The upper absorber connection is arranged so that relatively cool water coming from the absorber during periods of low insolation will not mix with hot water in the top of the tank. A booster, if provided, is placed about half way up the tank so that only water for the current days use is heated. Losses from a tank of this design amount to about 6 btu/hr per deg. F

of mean temperature difference between water and ambient. This is usually about 15-20 percent of the daily solar heat input. Additional insulation is not usually justified here, since it costs about the same as providing the same amount of energy by extra absorber area. A typical 70 gal tank is suitable for a small family (Fig. 77).

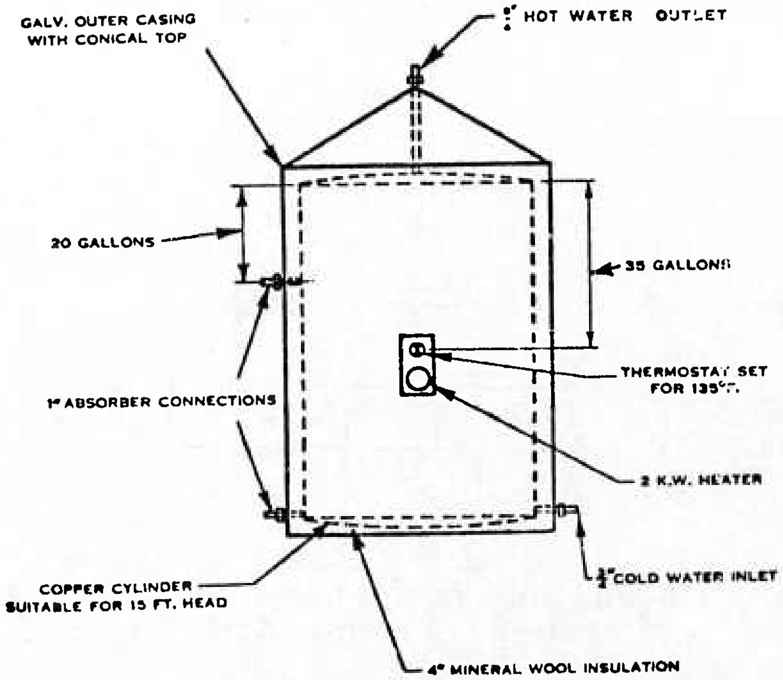


Fig. 77. Schematic of a 70 gallon outdoor hot water storage tank, Australia [64].

Various observations together with published Australian radiation records permit various system efficiencies to be determined for a solar water heater of this type comprising two 24 sq. ft. absorbers and a 70 gal tank from which 45 gal of hot water was withdrawn each day for 12 months. The calculated monthly efficiencies vary from about 30 percent in the winter to 40 percent in summer months, with an annual average of 35 percent.

To meet the popular demand in Australia for information on using this design in domestic installations, a circular was published in 1959 summarizing recommended practices. A typical domestic installation is shown in Fig. 78.

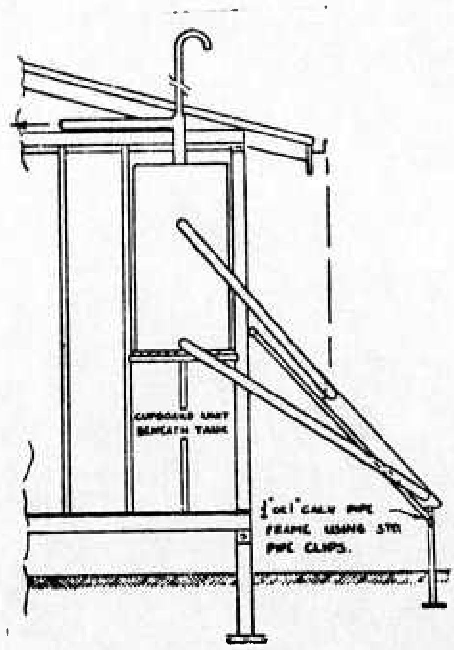


Fig. 78. Typical domestic installation showing storage tank supported on partition wall between two rooms, Australia [64].

In general, large installations require forced circulations; Fig. 79 shows the arrangement of such a unit in Canberra. The time switch ensures that the booster is off during the day, and the absorber pump which is controlled through a differential thermostat is off at night.

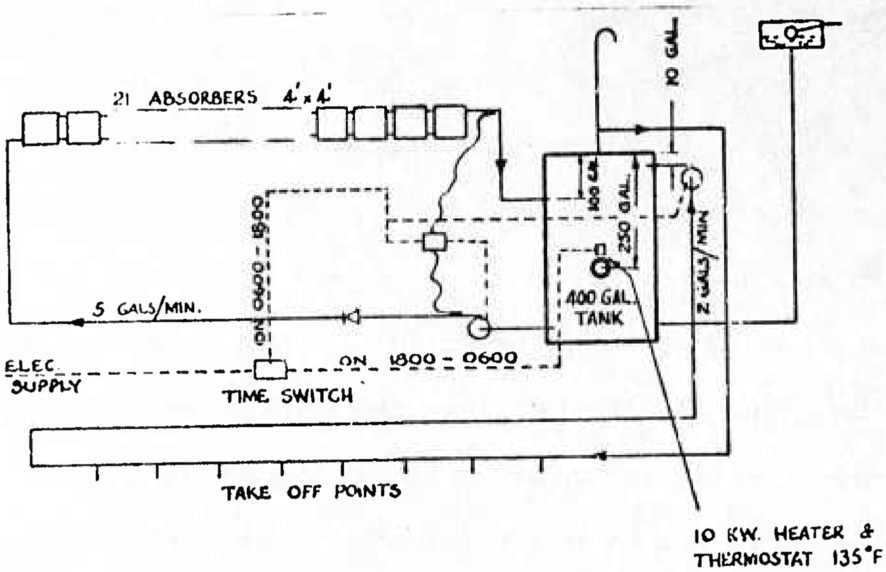


Fig. 79. Diagrammatic arrangement of a large solar water heater for a laboratory in Canberra, Australia [64].

Although a good deal of progress has been made, there is much remaining to be done, both from the point of view of research into cheaper and better ways of collecting solar energy and also into improving methods of manufacture. There are many areas where solar water heaters would be quite satisfactory from a functional point of view, the chief impediment to their widespread use being their costs. In Australia, if the cost could be reduced to one quarter of its present level, the solar unit would probably become the most widely used system for domestic water heating [64].

Egypt

Egypt has an enormous amount of sunshine compared with many other countries; on the average, only sixty days annually are cloudy or semicloudy around Cairo. The daily total direct and sky radiation incident upon a south-facing surface tilted 30° from horizontal at Cairo (latitude 30° North) during cloudless days varies from a maximum of about 2400 btu/sq ft/day during April to a minimum of about 2000 btu/sq ft/day during January. Thus, a 1 $m^2$ solar water heater of an overall efficiency of 70 percent can heat about 110 liters of water per day from an April average temperature of 21° C to 55° C, or about 80 liters of water per day from a January average temperature of 13.8° up to 55° C. The importance of these figures is apparent when the continuity of sunshine during at least 10 months annually, and the relatively high cost of other fuels used at present for water heating, are both pronounced.

In recent years additional types of Egyptian solar water heaters have been made, with their use confined to laboratory experiments. For units in use, the basin open-cycle type, characterised by its low cost, was found suitable for rural use, and the unit was standardized to be of 1 $m^2$ area and multiples. The metal-in-strip closed-cycle type, suitable to heat water for city and rural services, e.g., hospital, hotels, schools, private and public houses and for rural public washing facilities, is standardized to a 2 $m^2$ unit and multiples. For big installations, e.g., the university

city and the like, any size other than the standard sizes mentioned may be made in metal-in-strips. With the 2 $m^2$ metal-in-strip heater, the storage tank has a capacity of about 150 liters. A natural circulation (thermosiphon) system or forced circulation system with a pump controlled either thermostatically or by radiation may be used. The plastic "pillow" or "dish" type of solar water heater is also in its early stage of laboratory testing here [110].

Some details on the 2 $m^2$ metal-in-strip heater with forced water circulation are as follows. The heater is made of one corrugated galvanized iron sheet and a flat sheet, with the two sheets are riveted at several points along the lines of contact. The end edges are soldered to square headers made also of galvanized iron of thicker gauge. Cold water is let in at the lower end and flows up the channels (eight per meter) into the upper header. The flat sheet is 1 x 2 meters and about 0.50 mm thick. Two 3 mm thick glass covers are used with about 2 cm spacing. About 5 cm space exists between the lower glass cover and the flat iron sheet. The back insulation is glass wool of about 5 cm thick; the iron surface is blackened by a suitable method.

In one test reported, water at 22° C was pumped through the heater at different rates. Similar tests were made with heaters of areas of 4, 6 and 8 square meters. A 2 square meter solar heater may heat a daily average of 270 liters with a daily average temperature rise of

$25^{o}$ C., thus the useful daily heat energy obtainable from such a heater will be 6750 Kcal/day. A yearly figure corresponding to 300 days of sunshine in the Cairo area will be 2,025,000 Kcal/annum [110].

## France

France is one of the leaders in the field of solar water heater construction. The Radiasol Company of Paris and Casablanca, a relative newcomer, is now producing an ingenious and efficient device on a quantity basis.

The Radiasol systems have the obvious advantage of extremely low cost operation combined with low initial cost; besides eliminating the need for coal, oil or gas-fired boilers or electric heating coils, they don't need pumps to get the water up to the roof, provided there are existing pressure mains and suitable plumbing. To provide hot water in sunless periods, Radiasol offers a combination electric and solar energy heater which even with the additional cost of the electricity still affords a 90 percent reduction in costs from conventional water heating methods [20].

Radiasol offers a standard 200 liter, 2 $m^2$ water heater, serving a family of 2 to 4. It is a complete set, shipped from the factory in two cases and can be put into service immediately, provided there is a cold water header and a hot water distribution system (Fig. 80).

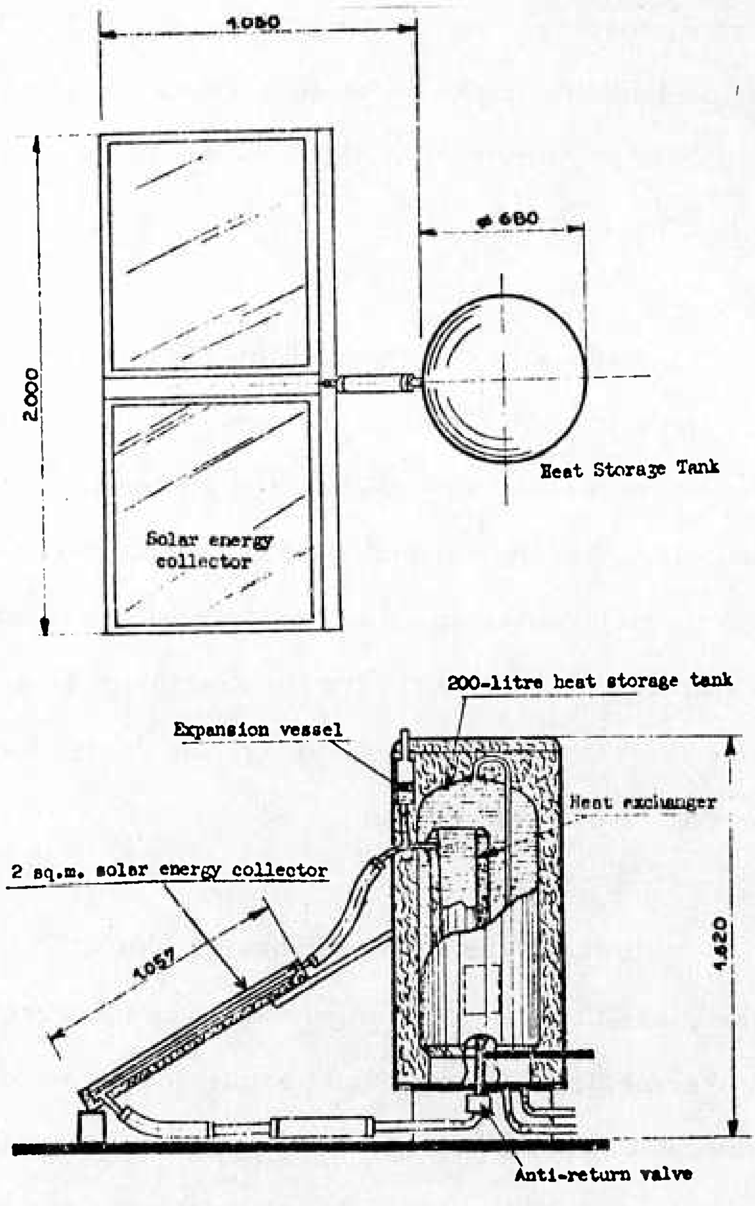


Fig. 80. Schematic of Radiasol water heater, France (dimensions in meters) [66].

Radiasol also markets equipment for large hot water plants (several cubic meters), comprising collectors of 2 $m^2$ for assembly into batteries, and storage tanks of various sizes (500, 750, 1,000, 1,500 and 2,000 liters) with a single or double heat exchanger, with or without a stand-by heating system.

Radiasol heaters used the greenhouse effect for collecting the heat. The 2 $m^2$ solar collectors consist of a flat reservoir, as the absorber, placed in an insulated box and glazed with a glass pane exposed to the sun. The absorber is connected to a heat exchanger placed in pressurized water contained in an insulated storage tank. The collectors are always arranged so as to recive the maximum solar radiation at noon. To transfer the heat to the water supply, the design uses either thermosiphon circulation or forced circulation.

In the standard water heater (200 l), as soon as the sunlight strikes the glass the water becomes heated in the absorber, the circulation starts by thermosiphon effect, and heat is delivered to the supply water through the heat exchanger. As soon as the sun disappears, the circulation stops and is irreversible, owing to the location of the collector (in tropical regions), or by the action of a patented Radiasol valve (in Mediterranean regions), which permits reducing the height of the equipment to the height of the storage tank (Fig. 80).

In the larger plants, with a capacity up to several tens of cubic meters, the storage tanks are placed in the basement of the building. In such cases, the thermosiphon principle can no longer be used to circulate the water, and a pump controlled by a patented Radiasol regulator is used instead (Fig. 81). The regulator automatically determines the period of the day when heat can be supplied to the volume of water to be heated. This forced circulation considerably improves the output of the process. Also, placing the storage tanks inside markedly diminishes the heat losses. Loads on the balconies or roofs are also considerably reduced in this way, so that the installation, the height of which is no more than 1.60 m in the Mediterranean region, is practically invisible from the ground. Finally, this unit method makes it possible to fit the plant exactly to the requirements. Since standard components are used, one may increase the heating surfaces and the number of capacity of the storage tanks on demand.

A new method of attaching the collector to the storage tank unit allows the inclination of the collector to be changed during the course of the year. This is accomplished by means of a collar sliding along the surface of the storage tank and a set of flexible connecting piping, permitting any inclination between $15^{\circ}$ and $45^{\circ}$.

Radiasol's solar water heaters with heat exchanger operating on the thermosiphon principle, are of two types. One type has the heat exchanger in a small tank attached to the bottom of the reservoir containing the water to

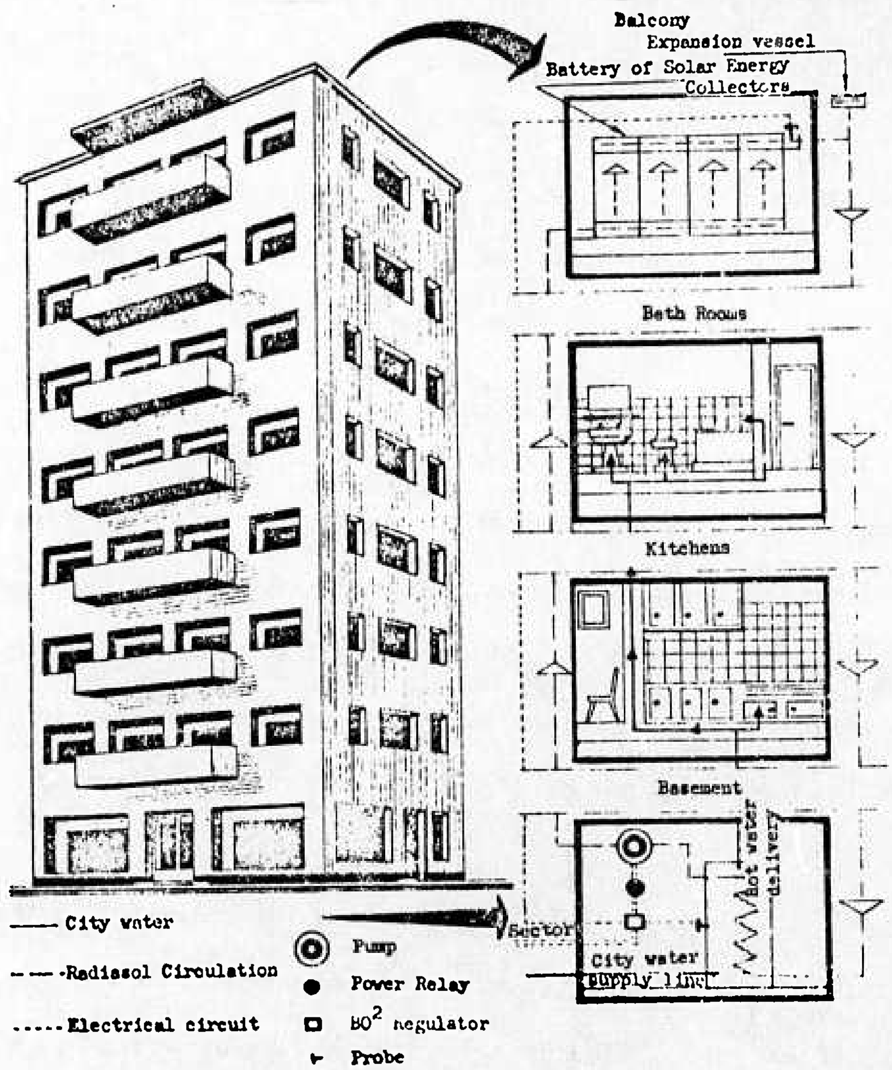


Fig. 81. Schematic diagram of a large-scale Radiasol hot water service [66].

be heated, with the collector installed below. The total height of the plant is the sum of the total heights of these three elements: tanks, heat exchanger and collector. This arrangement prevents return flow on the thermosiphon principle at night, but the total height of the plant involves many disadvantages such as esthetic considerations, ease of installation, ventilation, etc.

The other type has the heat exchanger inside the reservoir, and the collector is installed at the same height as the exchanger. In this case, the total height of the plant is much less than with plants of the former type, but under these design conditions there is a return thermosiphon effect at night, thus causing the storage tank to lose part of the heat stored in it during the day.

The Radiasol check valve prevents this reversal. In contrast to valves currently in use, it is sensitive to extremely low actuating pressures and does not substantially reduce them. The value comprises a moving mushroom element in a shell with inlet and outlet ports (Fig. 82). The mushroom is conical and is made of corrosion-resistant plastic with a coefficient of cubical expansion low relative to that of water. It is so weighted as to be in indifferent equilibrium when placed in the liquid used for the heating circulation.

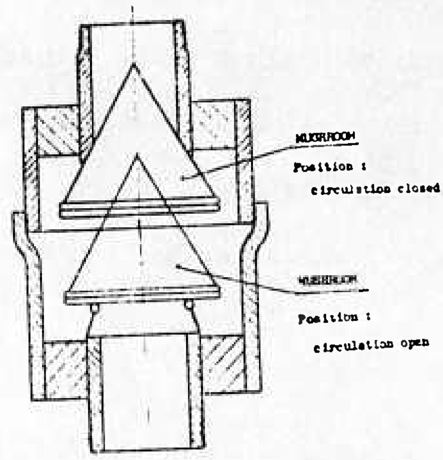


Fig. 82. Schematic diagram of Radiasol low pressure check valve [66].

When the reservoir and its exchanger are at the same level as the absorber, or below it, the circulation is obtained by a pump which operates only when the temperature of the fluid in the absorber is higher than the mean temperature of water in the reservoir. This control is provided by the Radiasol regulator, shown in Fig. 83. It consists of a D. C. generator feeding a Wheatstone bridge with one branch probe to sense the temperature of the solar collectors (the hot probe) and the other to sense the temperature of the reservoir (the cold probe). A temperature difference detector is placed across the diagonal of the bridge.

During rainy days, or days with very little sunshine, solar radiation may be insufficient to obtain the minimum temperature required

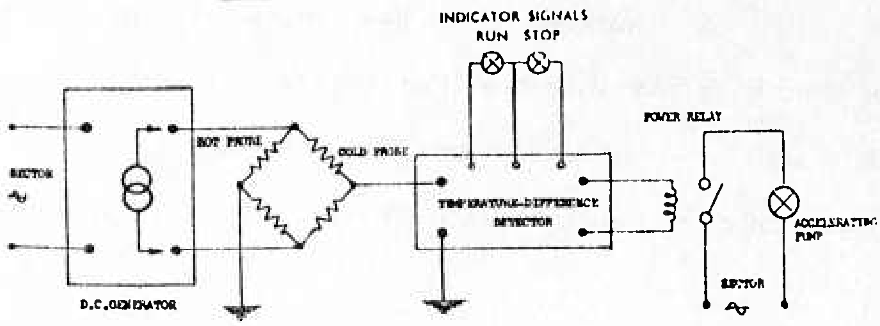


Fig. 83. Schematic diagram of Radiasol $BO^2$ regulator* [66].

in the reservoir. Such periods are very infrequent in a desert climate, and do not exceed several tens of days per year, for example, in the Mediterranean climate. Radiasol accordingly provides a stand-off heating system in all cases where uninterrupted hot water service is essential. The stand-by electric system for the standard Radiasol water heater of 200 liters/$2m^2$ is controlled by a thermostat and a clock, which will permit the electric circuit to close only when the temperature of the reservoir water is below $50^{\circ}$ C, and at night, to gain the benefit of the night electric rates where they apply.

Stand-by heating for the large Radiasol forced-circulation solar water heaters has several options:

o As with the standard 200 liters/2 $m^2$ water heater, an appropriate electrical resistance may be placed in the last reservoir of the plant;

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* $BO^2$ - trade name for the temperature sensitive electronic device.

o When the house has central heating, the last reservoir of the plant may have two heat exchangers, one with a large heating surface for the solar heating circulation, the other with a normal heating surface branching onto the central heating system like a simple radiator; and

o A gas water heater may be placed at the output of the solar heating plant. Again, the burner of this heater will light only if the water heated by solar energy fails to reach the desired temperature [66].

We may note in conclusion that seventy percent of the total business of the Radiasol Company is for plants serving public buildings; these now include hotels, clinics, maternity hospitals, dispensaries, athletic clubs, military barracks, boarding schools, religious communities, and others.

India

In India, considerable attention has been devoted to developing an economic and efficient design for a solar water heater. One such large-size solar water heater, designed and tested in India, is composed of a flat-plate solar collector, storage, circulation system and an auxiliary heating system [54].

The flat-plate collector in this design is very simple to operate, easy to manufacture and low cost, absorbing diffuse as well as direct solar

radiation. The collector consists of 28 gauge aluminum sheet blackened on the exposed side and attached to a set of galvanized pipe of 19 mm in diameter with 10 cm spacing to provide good thermal contact between the tube and the plate (Fig. 84(a)). The recommended collector configuration has been optimized on the basis of maximum efficiency per unit cost. It is enclosed in a box containing glass wool or fiber glass insulation which has a glass window on the exposed upper side (Fig. 84(b)).

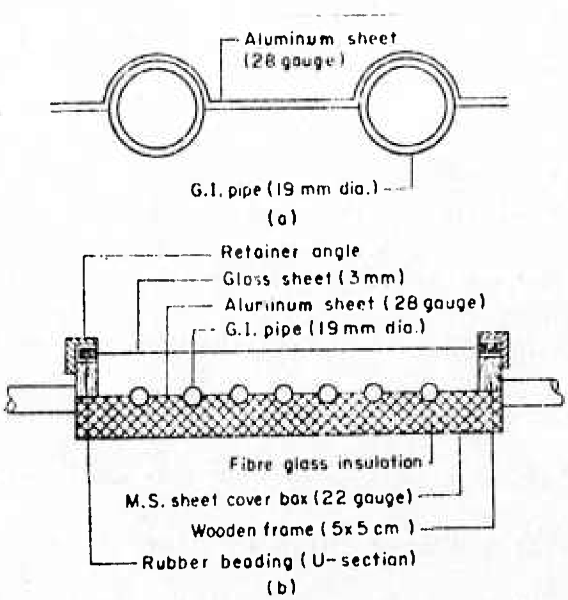


Fig. 84. Schematic of (a) contact bond type flat plate collector and (b) cross section of collector unit, India [54].

The collectors are made in two sizes: 1.2 x 0.75 m and 1.83 x .75 m. These dimensions were selected so that two persons could handle them easily. Furthermore, the size conforms to standard sizes of metal sheet available in the market. Any number of these can be connected to provide the total

area required, depending on insolation conditions for a given locale. The absorber areas for various water capacities and temperatures for several cities in India are given below:

| Amount of water | | Delhi | | | Poona | | | Calcutta | | | Madras | | | Roorkee | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| gallons | litres | 50°C | 55°C | 60°C | 50°C | 55°C | 60°C | 50°C | 55°C | 60°C | 50°C | 55°C | 60°C | 50°C | 55°C | 60°C |
| 30 | 137 | 2·07 | 2·43 | 2·85 | 1·50 | 1·80 | 2·13 | 2·34 | 2·79 | 3·27 | 1·14 | 1·71 | 2·04 | 1·98 | 2·43 | 2·70 |
| 40 | 182 | 2·76 | 3·24 | 3·80 | 2·0 | 2·4 | 2·84 | 3·12 | 3·62 | 4·36 | 1·88 | 2·28 | 2·72 | 2·64 | 3·24 | 3·60 |
| 50 | 227 | 3·45 | 4·05 | 4·75 | 2·50 | 3·0 | 3·55 | 3·90 | 4·6 | 5·45 | 2·35 | 2·85 | 3·40 | 3·30 | 4·05 | 4·50 |
| 60 | 273 | 4·14 | 4·86 | 5·70 | 3·0 | 3·6 | 4·26 | 4·68 | 5·58 | 6·54 | 2·82 | 3·42 | 4·08 | 3·96 | 4·86 | 5·40 |
| 70 | 318 | 4·83 | 5·67 | 6·65 | 3·50 | 4·20 | 4·97 | 5·46 | 6·51 | 7·63 | 3·29 | 3·99 | 4·76 | 4·62 | 5·67 | 6·30 |
| 80 | 364 | 5·52 | 6·48 | 7·50 | 4·0 | 4·80 | 5·68 | 6·24 | 7·44 | 8·72 | 3·76 | 4·56 | 5·44 | 5·28 | 6·48 | 7·20 |
| 90 | 409 | 6·21 | 7·29 | 8·45 | 4·50 | 5·4 | 6·39 | 7·02 | 8·37 | 9·81 | 4·23 | 5·13 | 6·12 | 5·94 | 7·29 | 8·10 |
| 100 | 454 | 6·90 | 8·10 | 9·50 | 5·1 | 6·0 | 7·10 | 7·80 | 9·10 | 10·9 | 4·70 | 5·70 | 6·80 | 6·60 | 8·10 | 9·00 |
| 120 | 545 | 8·28 | 9·72 | 11·40 | 6·0 | 7·20 | 8·52 | 9·36 | 11·16 | 13·08 | 5·64 | 6·84 | 8·16 | 7·92 | 9·72 | 10·80 |
| 130 | 590 | 8·97 | 10·35 | 12·35 | 6·50 | 7·80 | 9·23 | 10·14 | 12·09 | 14·17 | 6·11 | 7·41 | 8·84 | 8·58 | 10·53 | 11·70 |
| 140 | 635 | 9·66 | 11·34 | 13·30 | 7·00 | 8·40 | 9·94 | 10·93 | 13·02 | 15·26 | 6·58 | 7·98 | 9·52 | 9·24 | 11·34 | 12·60 |
| 150 | 681 | 10·35 | 12·15 | 14·25 | 7·50 | 9·0 | 10·65 | 11·78 | 13·95 | 16·35 | 7·05 | 8·55 | 10·20 | 9·90 | 12·15 | 13·50 |
| 160 | 726 | 11·04 | 12·96 | 15·20 | 8·00 | 9·60 | 11·36 | 12·48 | 14·88 | 17·44 | 7·52 | 9·12 | 10·88 | 10·56 | 12·96 | 14·40 |
| 170 | 772 | 11·73 | 13·77 | 16·15 | 8·50 | 10·20 | 12·07 | 13·26 | 15·81 | 18·53 | 7·99 | 9·69 | 11·55 | 11·22 | 11·77 | 15·30 |
| 180 | 817 | 12·42 | 14·58 | 17·01 | 9·00 | 10·80 | 12·78 | 14·04 | 16·74 | 19·62 | 8·46 | 10·26 | .2·24 | 11·88 | 14·58 | 16·20 |
| 190 | 862 | 13·11 | 15·39 | 18·05 | 9·50 | 11·40 | 13·49 | 14·82 | 17·67 | 20·71 | 8·93 | 10·83 | 12·92 | 12·54 | 15·39 | 17·10 |
| 200 | 908 | 13·80 | 16·20 | 19·00 | 10·00 | 12·00 | 14·20 | 15·60 | 18·60 | 21·80 | 9·40 | 11·40 | 13·60 | 13·20 | 16·20 | 18·0 |



The size of the storage tank depends on the daily demand for hot water and on the radiation intensity locally available. A vertical cylindrical storage tank of height about twice the diameter is typically chosen. The tank has 10 cm thick fiber glass insulation, which is further protected by a sheet steel cover. A 3.0 kw immersion heater and a safety thermostat are also fitted into the storage tank. The cold water enters the tank at the bottom through a pipe connected to a float valve system. The hot water pipe takes off 30 cm below the water level to ensure a good flow rate.

The Indian solar water heater described may work at full pressure, if desired, in the following three ways;

o The absorber and the storage tank both operate at low pressure, and the cold water passes through the heat exchanger coil in the tank to be heated,

o The absorber operates at low pressure with a heat exchanger coil in the tank which is at mains pressure, or

o The absorber and tank are both at direct mains pressure.

In large-size heaters it is impractical to mount the storage tank above the absorbers, so a forced-circulation system is used. Here the tank can be located at any convenient place, not necessarily near the absorbers. The tank may be of large size with water circulated by means of a booster pump. Two methods are commonly used for pump control operation: temperature-set control and radiation-set control. In the former, a reverse-type thermostat set at the desired temperature is fixed at the outlet of the collector (Fig. 85). The pump switches on automatically

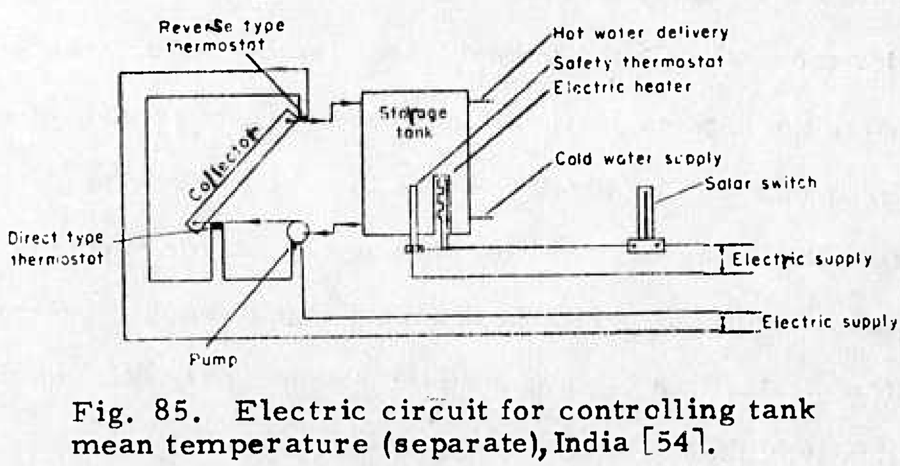


Fig. 85. Electric circuit for controlling tank mean temperature (separate), India [54].

when the outlet temperature equals or exceeds the set temperature of the thermostat. In the radiation-set control device, the pump is switched on by a radiation-sensing element, e.g. photocell, set for a particular radiation intensity; this type of control requires frequent inspection and maintenance.

In order to improve efficiency a differential circuit has been developed and tested in a prototype unit. In this circuit, the reverse-type thermostat is connected in series with a direct-type thermostat at the inlet of the collectors; these are then connected in series with the pump. It is assumed that the tank mean temperature is equal to the inlet temperature; thus the pump circulates water only when the outlet temperature equals or exceeds the set temperature and the water temperature in the tank has not reached the desired level. This control method has the advantage that heat energy is added to the system whenever it is available. The complete circuit is shown in Fig. 85.

The design of a solar water heater can be based either on the availability of maximum radiation (summer months) or of minimum radiation (winter months). In the former case, the collector area will be less, thereby reducing the capital cost, but the heater will have poor efficiency during winter months. The ideal would be to base the design on minimum radiation received on clear days and to make provision for supplementary and continuous supply of extra heat during cloudy days. Therefore, an auxiliary electric heater has been used in the present case, though the capital cost is slightly higher.

For controlling operation of the immersion heater, time switches are usually employed which keep the heater disconnected during a pre-set time interval (generally from sunrise to sunset). However the concept of time switch fails when clouds appear during daytime and there is intermittent demand for hot water; to overcome this difficulty, a solar switch for the heater has been added, and is nominally set at 40° C. Thus on clear days in winter, it will only disconnect the electric circuit from 9:00 a.m. to 4:00 p.m. which is the solar heating time. The details of the circuit are shown in Fig. 86.

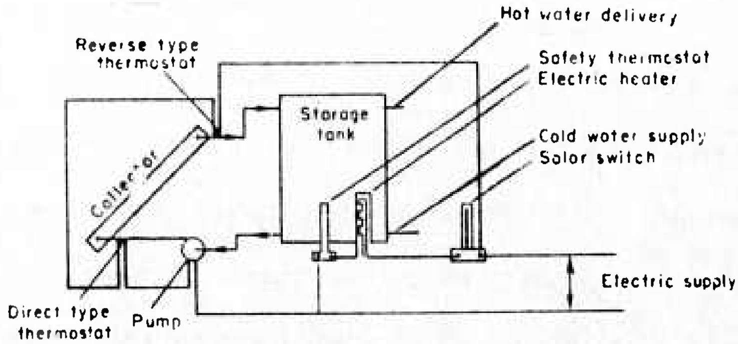


Fig. 86. Electric circuit for controlling tank mean temperature (combined), India [54]

The normal daily hot water requirement of this Indian system has been assessed at about 600 liters for twenty people at a temperature ranging between 45 and 50° C. The absorber area for this requirement is calculated as 8.5 $m^2$; in a system described, six absorbers, each having an area of 1.37 $m^2$, were connected in parallel as seen in Fig. 87. The flow

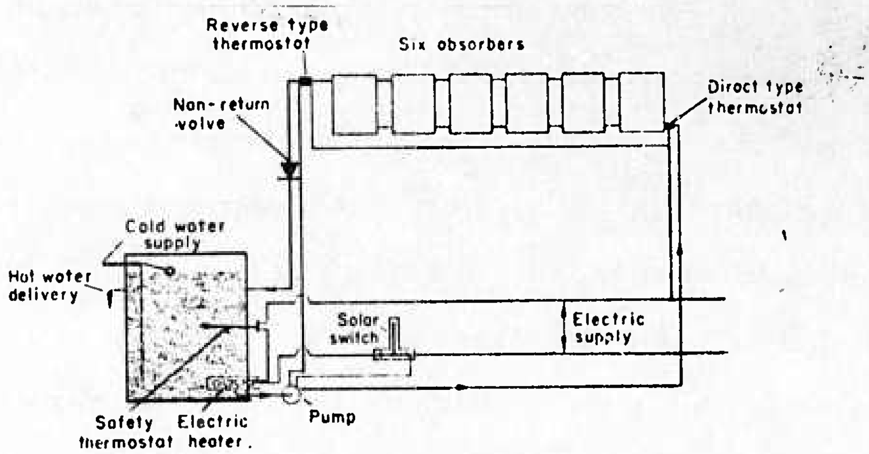


Fig. 87. Typical forced circulation hot water heating system, India [54].

rate will not affect the performance of the system greatly, since the control is intermittent and water circulates through the absorbers only when the outlet temperature is greater than the tank mean temperature. A 1/6 hp pump has been found adequate to maintain a flow rate of 10 l/min, which is nearly the same as in natural circulation type solar water heaters. Reverse circulation is checked by a non-return valve in the circuit (Fig. 87).

Performance tests on a fully-automatic prototype unit of this kind were conducted at Roorkee during two winter seasons. It was observed that the maximum mean tank temperature was 55° C, dropping only to 48°-50° C the next morning without resorting to the use of the immersion heater in the tank. Full details on performance are given in the following table:

| Date | Time (hours) | Water temperature (°C) | Total heat collected (kcal) | Total Insolation on absorber (kcal) | Efficiency of collection (per cent) | Water temperature next day (°C) 8·0 a.m. | Electric energy consumed by pump per day (kWh) |
|---|---|---|---|---|---|---|---|
| 28th Nov. 68 | 8·0 a.m.<br>4·0 p.m. | 20·0<br>56·0 | 21,600 | 43520 | 49·6 | 51·0 | 0·24 |
| 20th Dec. 68 | 8·0 a.m.<br>4·0 p.m. | 18·0<br>56·0 | 22,800 | 43816 | 52·0 | 50·0 | 0·22 |
| 16th Jan. 69 | 8·0 a.m.<br>4·0 p.m. | 17·0<br>55·0 | 22,800 | 43936 | 51·8 | 48·0 | 0·25 |
| 15th Feb. 69 | 8·0 a.m.<br>4·0 p.m. | 18·0<br>54·0 | 21,600 | 43722 | 49·4 | 48·0 | 0·21 |
| 24th Nov. 69 | 8·0 a.m.<br>4·0 p.m. | 18·0<br>55·0 | 23,200 | 43500 | 51·0 | 49·0 | 0·23 |
| 23rd Dec. 69 | 8·0 a.m.<br>4·0 p.m. | 17·0<br>55·0 | 22,800 | 43819 | 52·3 | 50·0 | 0·25 |
| 8th Jan. 70 | 8·0 a.m.<br>4·0 p.m. | 15·0<br>55·0 | 24,000 | 43960 | 54·5 | 49·0 | 0·25 |

It can be seen from the table that the collection efficiency averaged around 50 percent. The power consumed by the pump was only about 0.23 kwh per day, or about 7.0 kwh per month [54].

The National Physical Laboratory of India jointly with the Central Scientific Instruments Organization, New Delhi, has also conducted diverse research on various solar water heaters [111]. Their developments include a cheap and improved type of collector.

In most of the common types of flat plate collectors tried in other countries, the heat transfer is effected by water flowing through

copper pipes soldered to a blackened copper absorber plate. This method suffers from certain obvious disadvantages, which reduce the efficiency of heat transfer. In the first place, the copper pipes fixed to the absorber are usually spaced about 4 to 6 in. apart and it is found that midway between two adjacent pipes the temperature is considerably higher than the temperature of the water-carrying pipes, which means a loss in efficiency. A second factor which reduces efficiency is the very limited area of contact between the circular pipe and the flat surface of the plate, where the pipe is soldered to the plate with soft solder.

In view of the above disadvantages, Indian designers decided to do away with copper pipes altogether and to substitute corrugated metal sheets as heat collectors, backing them up with a plane metal sheet to form a sandwich with parallel water channels running the entire length of the corrugated sheet. Corrugated galvanized iron sheets are one of the cheapest roofing materials in India and are usually available in widths of 2-10 inches varying in length from 6 ft to 10 ft. These sheets are available in several thickness but it was found that 26 gauge (0.019 inch thickness) is the most convenient to handle.

Details of the sheet assembly and fastening are given in [111]. To complete the heating unit, the corrugated face is given a coating of carbon black. The completed assembly is encased in a wooden box large enough to allow 4 in. of rock wool insulation at the bottom and around all sides. To

prevent shadows an extra space of 4 in. is allowed on the two long sides and wooden planks painted white are fixed at a small angle to the sides. The upper face of the box is glazed with sheets of 1/8 in. thick window glass, with an air gap of about 2 in. between the glass sheets and the metal heater surface. The heater units thus formed have a glazed surface area of 22.4 sq ft and blackened sun collecting area of 19.0 sq ft. The system as installed for domestic hot water supply is shown in Fig. 88, and details of the collector are given in Fig. 89.

In order to get maximum advantage of sunlight an adjustable arrangement is necessary for tracking the sun. An elaborate arrangement of this type would be cumbersome and expensive, hence a compromise had to be made to fix the collector in a position of maximum advantage. This can be done in the northern hemisphere by facing the collector due south and inclining the surface at an angle to the horizontal equal to the latitude of the locale. This will ensure normal incidence at midday at the periods of the equinoxes, when the sun is low in winter and high in summer. However, in order to make the best use of the winter sun, when the length of the day is short and the hot water requirements are large, it was decided instead to set the collector at an inclination of $45^{o}$ (latitude of Delhi, $28^{o}35'$). This ensures a larger amount of solar intensity during the winter months.

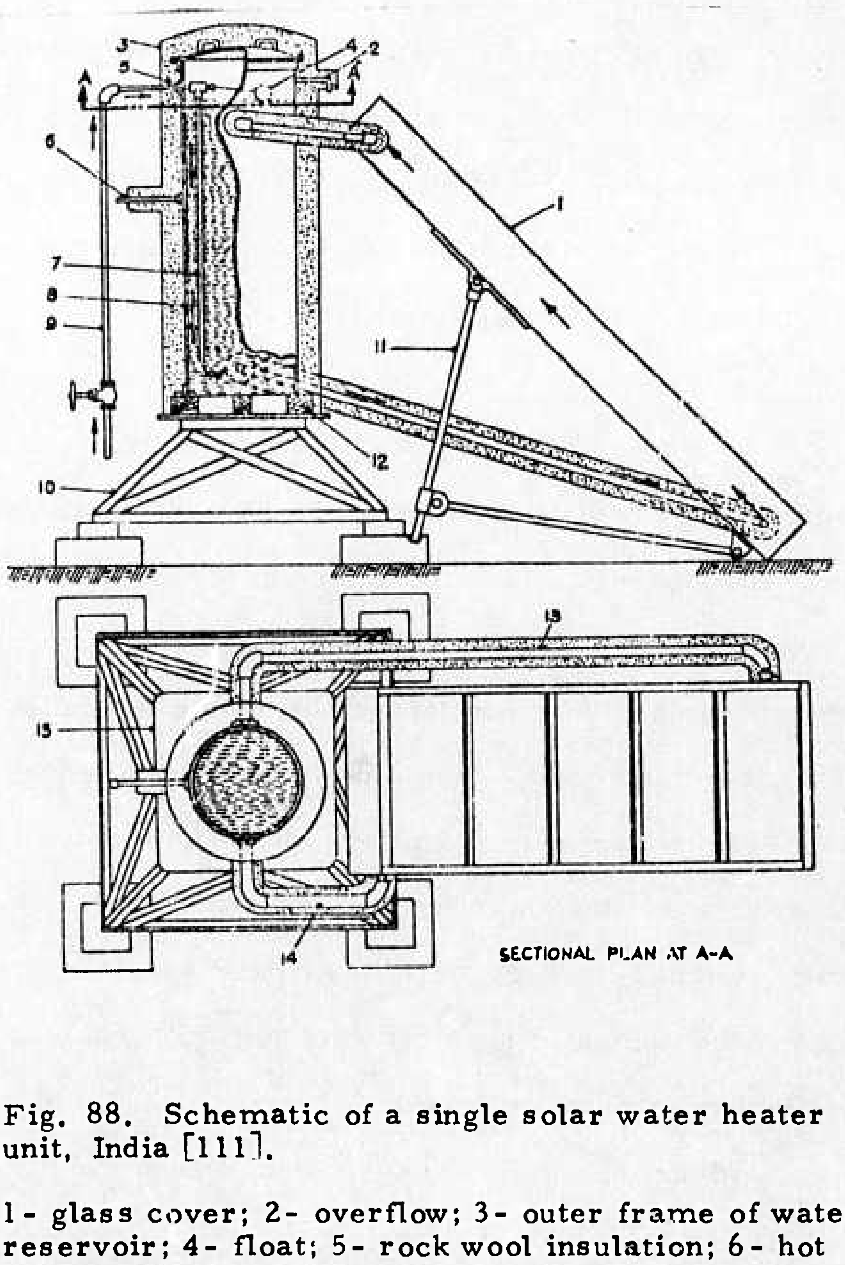


Fig. 88. Schematic of a single solar water heater unit, India [111].

1- glass cover; 2- overflow; 3- outer frame of water reservoir; 4- float; 5- rock wool insulation; 6- hot water outlet; 7- cold water inlet; 8- wall of water reservoir; 9- connection to water supply; 10- stand; 11- support for collector; 12- wooden base for reservoir; 13- cold water inlet pipe; 14- hot water outlet pipe; 15- outer frame of water reservoir.

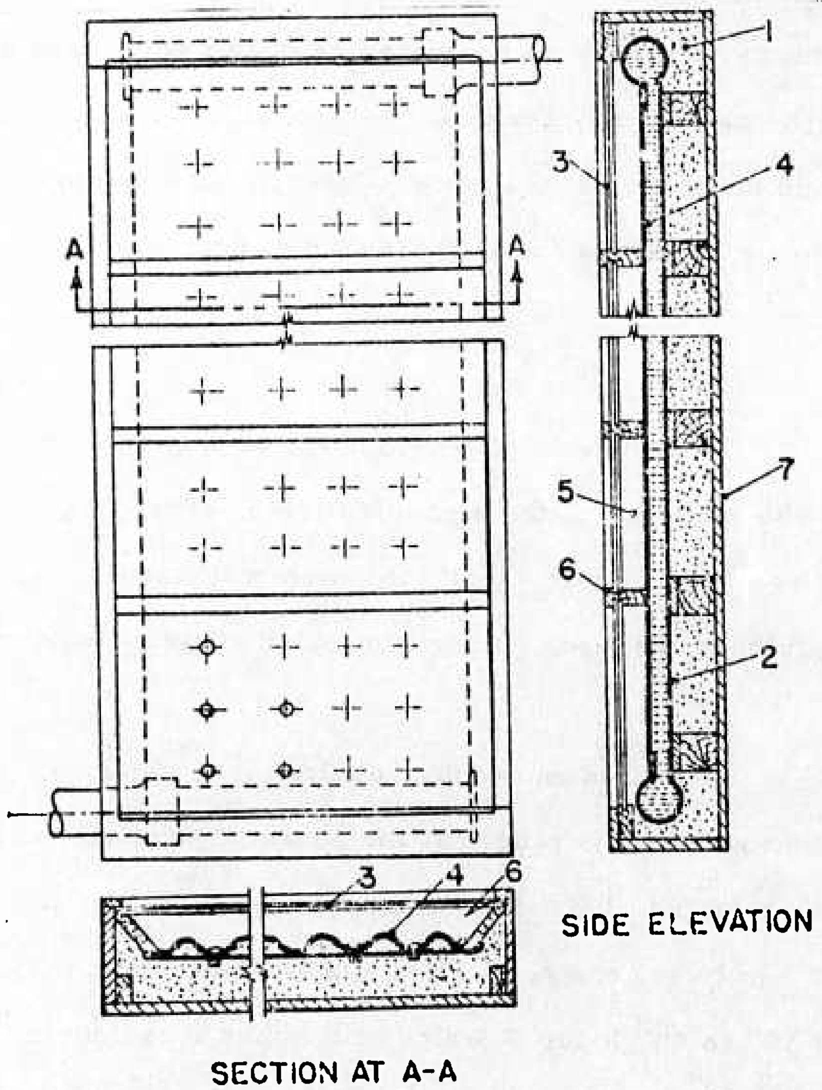


Fig. 89. Schematic of solar water heater collector, India [111].

1 - rock wool insulation; 2 - bottom plane sheet;
3 - glass sheet cover; 4 - top G. I. corrugated sheet;
5 - air gap; 6 - felt padding; 7 - wooden casing.

This heating system has been installed on the roofs of several houses, with care taken that sufficient pressure exists in the supply line to refill the storage tank as hot water is drawn out. If owing to low pressure during the day the storage tank does not fill, then the thermosiphon action stops and no heating takes place. In such cases a cold water tank at a somewhat higher level was found necessary to keep the storage tank full at all times.

The main point about the arrangement adopted here is the low cost of the system and the higher collector efficiency compared to the copper pipes fixed over copper sheet, as commonly used. The efficiency for this Indian system averages 80 percent under certain conditions.

Based on testing results, it is clear that the design of this solar water heater is practical for obtaining a supply of hot water. In the size investigated, i.e., an insolation area of 22 sq. ft., an optimum supply rate of 7 to 10 gallons per hour could be maintained with a temperature rise of $38^{\circ}$ to $50^{\circ}$ F for a period of 6 hours a day during the winter months in Northern India (excepting a few cloudy days during late December and early January). Over a 6-hour period the energy absorbed for a 22 sq ft insolation area averages between 20,000 and 26,000 btu per day, corresponding to slightly over 6 kw hr of electrical energy.

It is emphasized [111] that in the arrangement adopted here an effort has been made to keep the cost as low as possible. The cost of materials and labor for a unit using two 22 sq ft insolation cabinets and an insulated storage tank of 100 gallon capacity comes to 500 rupees or about 60 dollars. To this must be added the cost of pipeline and its insulation from the storage tank to the points of consumption. If the demand for hot water is not large, then only one heating unit of 22 sq ft area need be used with a 60-gallon storage tank. This will bring down the first cost to about 350 rupees ($44) which is about two-thirds the cost of a comparable electric heater with the added advantage that there is no recurring cost of energy. Several of these units have been under experimental use for several years and have proved entirely satisfactory [111].

Israel

Solar water heaters were first offered for sale in Israel by Miromit Sun Heaters, Ltd. of Tel-Aviv, some 16 years ago. Since then, solar water heaters have become a widely used and very popular means of heating water for homes, hospitals and industry. There are many thousands of solar water heaters in use in Israel and being exported to more than twenty countries (Nepal, Kenya, Cameroon, Ethiopia, Mali, Honduras, Philippines, Iran, Turkey, Chile, Mexico, Argentina, Portugal, Greece, Spain, Switzerland and others).

A Miromit solar collector of 1.5 $m^2$ is connected to a storage tank of 120 liters. The storage tank, being in excess of the optimum output of the collector (approx. 5000 kcal/day) stores almost 100% of the heat output of the latter. Connections between collector and tank are as short as possible and well lagged. The flow of the thermosiphon is adjusted to give a maximum temperature of 65° C by a hand-regulated valve in the hot water return pipe.

To evaluate the performance of this system, at the end of the day (5 p.m.) all the water is drained from the insulated tank and for each 5 or 10 liters the temperature is registered. The difference between the temperature of the cold water in the supply line and the registered temperature gives the heat gain in kcal for each unit volume; the total daily heat output of the unit is then the total of all unit sums.

Such tests were performed during 14 months on two or three parallel and identical units. The results showed an interesting pattern: in summer (June-September) with solar radiation of 5,000-7,000 kcal/$m^2$ and water output temperature of 60 to 65° C, the conversion efficiency is approximately 35-45 percent, while in winter (December-March) with lower insolation (3,000-4,000 kcal/$m^2$) and slightly lower water output temperatures (50-60° C), the conversion efficiency was 50-60 percent.

This results in a levelling out of the annual collector output in relation to available insolation, which in Israel is in December approximately, one-third of the maximum (July) insolation. Thus, to ensure an even level of performance, the unit must be built in such a way that it can adjust its operation automatically to higher temperatures in the summer. Another means of compensating for differences in insolation is the angle of inclination of the collector, which should be nearer to an angle of $90^{\circ}$ in relation to the rays of the lowest winter position of the sun. A third factor, which became apparent in Israel after several years of experience, is the function of the dust cover as a filter in the summer months. This is particularly important in countries like Israel without summer rains, where the first few rains at the beginning of winter will wash off the dust and therefore raise the output during the shorter and colder winter days.

The Israelis have done a great deal of work in the theoretical analysis and practical development of flat-plate collectors of different capacities, with a view to reducing losses by improving insulation and increasing absorption. With several additional refinements in the manufacturing process, quite efficient collectors now may be produced. Israeli manufacturers claim that locally produced solar heaters achieve a 40% efficiency in converting solar energy [69].

Israeli scientists found problems of blackboard paint cracking, peeling, and flaking off after a few years, especially at higher temperatures on materials such as copper, aluminum, or galvanized sheet.

In addition, ordinary black metal sheets developed rust from condensed moisture in the collector. The color of blackboard paint tended to become grey and lost a great deal of its absorptive properties. A dull, sprayed, black paint is an alternative, but does not yield a smooth surface, so it is difficult to clean the dust which penetrates into the paint coat. The introduction and use of a selective blackened surface for collectors in 1959 has improved performance and solved some of the problems. The selective blackened collector plates are superior not only in their optical properties but in many other respects as well, which originally were not anticipated, e.g., the stability of color, the possibility of cleaning such surfaces, and their resistance to high temperatures.

While the standard size of solar water heater boiler in Israel is 120 liters, an 80 liter boiler is commonly used in Cyprus, Greece, Portugal, and Spain. One factor here is that the times of the day in which hot water is in use vary, and it is therefore important to know these demand hours for the planning of a hot water system. In some countries it is customary to bathe in the afternoon (Israel, Italy, Nigeria, Ghana), while in other countries, because of different working hours, hot water is mainly used during the morning (Portugal, Spain, Kenya, South Africa). Fig. 90 shows an Israeli installation in Kenya.

Fig. 90. An Israeli solar water heater in Isolio, Kenya. Storage tank (200 liters capacity) is in the tower [113].

There are certain uses for solar water heaters in which efficiency is particularly high, for example in institutions or factories where the total quantity of hot water is used at the end of the day. In such cases the solar water heaters will operate during the whole day at their best, without any heat losses during prolonged periods of night storage. Solar water heaters have been installed in Israel at service stations, factories and at an agricultural school for showering after work (4 to 6 p.m.).

with excellent results and at a relative low initial investment. The same can apply to army camps where the hours of use can be controlled.

The Miromit Company has planned and installed many large solar water heating units, such as a 2000 liter system with 40 collectors for a hospital (Fig. 91), and a 3000 liter unit with 50 collectors for an agricultural college (Fig. 92).



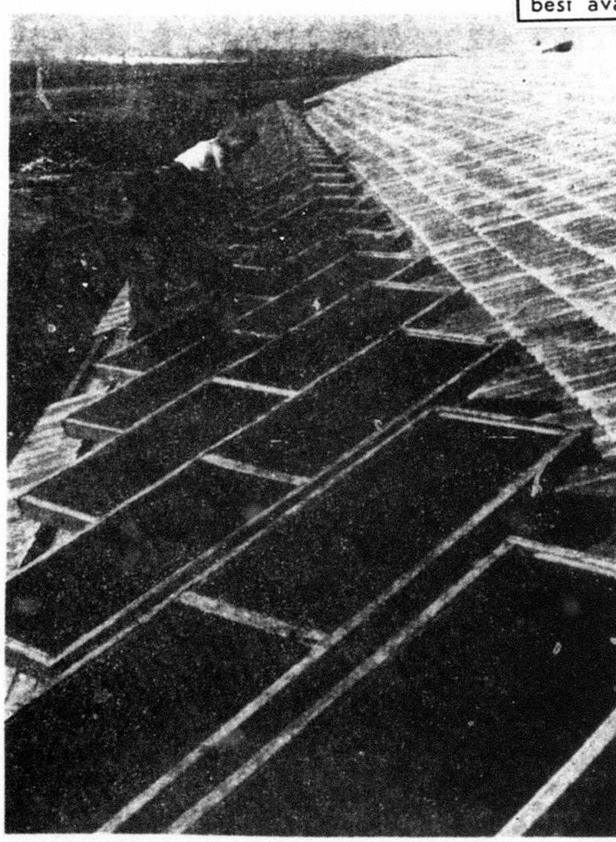

Fig. 91. Roof of a hospital with 40 collectors, Israel. Group of 10 is connected to one 500 liter boiler [113].

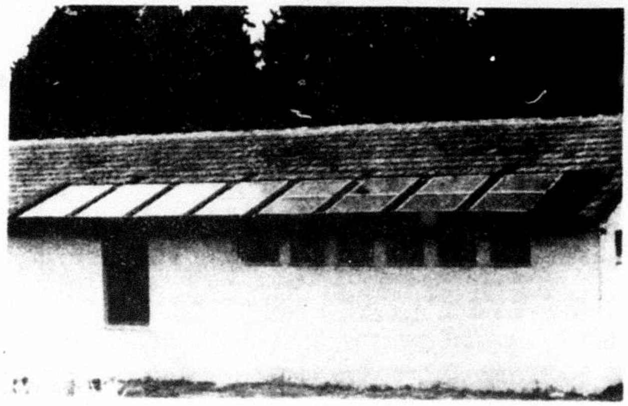

Fig. 92. Installation of 8 collectors connected to two 300 liter boilers Israel. This section of the roof is part of an installation of six such units of an agricultural college, [113].

The possibilities of planned, integrated solar roofs of 100 $m^2$ or more are being considered which could open up architectural and engineering possibilities in residential areas. If solar water heaters were to be included in the original building plans and installed before the house is finished, the time for installation clearly could be reduced. At present, most solar water heaters are installed after the building is finished, which involves separate transport, lifting and connecting of the units (Fig. 93 and 94).

The local customs and habits of the population have been considered by Israeli designers in planning the size of storage tanks and in the installation of the collectors. The solar water heater will influence the

Fig. 93. Two solar collectors mounted on the southern front wall of a villa, Israel. The storage tank of 200 liter capacity is under the roof [113].

way of life in many underdeveloped areas where the use of hot water for domestic purposes is at the moment very limited or unknown. The opening up of such markets by the gradual importation, assembly, and eventually, the local manufacture of licensed solar water heaters will be one future aim.

Meanwhile the experience gained in the planning, manufacture and installation of solar water heaters in Israel and many other countries permits a very optimistic view about future expansion in this field [113].

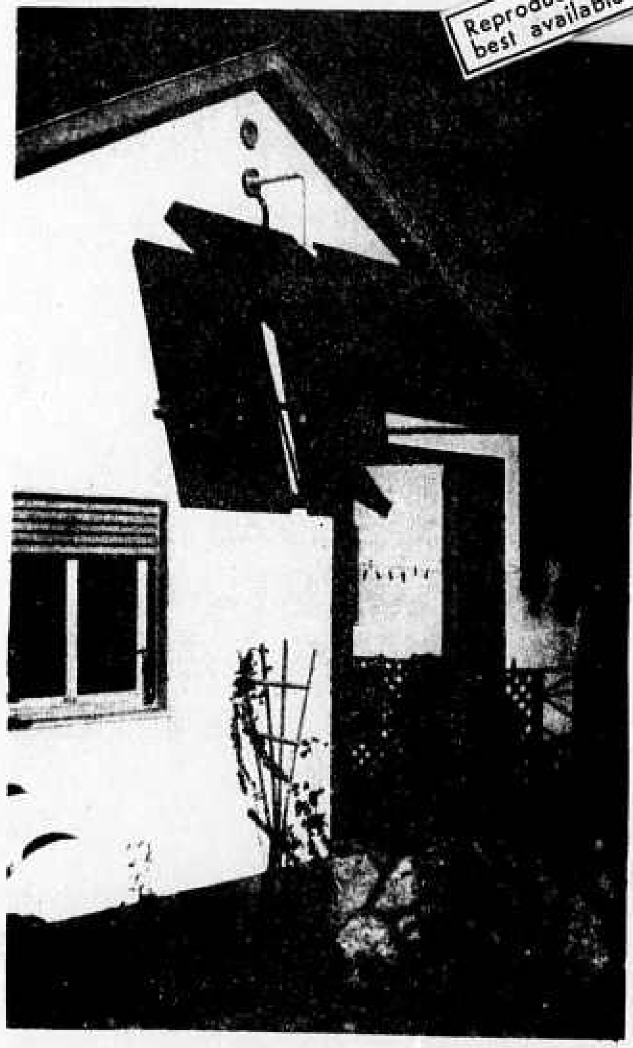

Fig. 94. Two solar collectors installed on the wall of a house, with storage tank inside the roof, Israel [113].



Japan

The main objective of the solar water heater in Japan is not for space heating but to supply hot water to a family bath, of which there were about fifteen million in use in 1969 serving some 65 percent of all houses. An open-type solar water heater was produced in central Japan about 25 years ago. Now being competitive with other fuel costs, it is estimated that some

2 million solar water heaters have been installed, equal to 26-27 percent of the bath installations in 1970. This nationwide trend is probably supported by a national predilection toward bathing because of high humidity; approximately one-third of these baths have been installed in farmhouses.

Most of the recent solar water heaters, now manufactured by six representative companies, are of the closed type, the remainder being of the natural circulation type. The former consists of cylindrical heat absorbers made of polyvinylchloride or stainless steel pipes insulated with a foam polystyrene layer. The latter type, made of galvanized iron or stainless steel pipes, has also come into the market.

Poly-Vinyl Ltd., of Osaka, markets several models of plastic pillow-type solar water heaters. Model No. 3, measuring 7 ft x 3 ft x 4 in. with 240 liters capacity, has a weight of 3.5 kg (including transparent hood and detachable metallic ribs). In 1961, over 300,000 units of this type were in use in Japan. Two other plastic pillow-type solar water heaters of small capacity are also marketed: Model No. 1, 38 gal capacity and 2.5 kg overall weight, and Model no. 2, 44 gal capacity and 3 kg overall weight. The plastic pillow-type solar water heaters are well suited to various outdoor activities where there is a great need for hot water and plenty of sunshine but limited supplies of fuel [112].

Broken down in more detail, the various kinds of solar water heaters now in use in Japan are the open-type, closed-type, closed-membrane type natural-circulation type, and once-through type of which the closed-

membrane type is the cheapest and most widely used, followed by the open-type and the closed-type. The natural-circulation type is not much used now, but its use will increase in the future.

An open-type solar water heater 0.9 m wide, 2 m long, and about 0.15 m deep, is illustrated in Fig. 95. The inside bottom and side

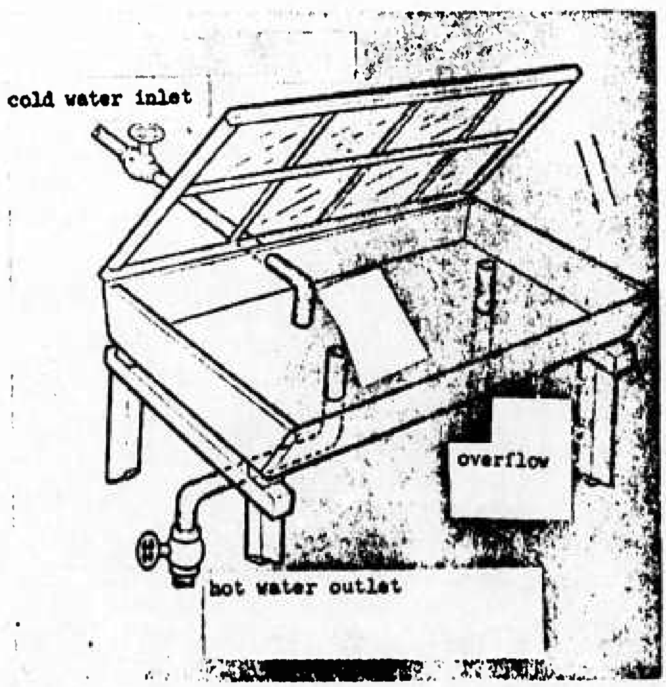


Fig. 95. Open-type solar water heater, Japan [114].

surfaces are covered with black vinyl membrane, and the upper surface is covered with glass plate. It is filled with water to a depth of about 0.11 meter. Because this type of heater is simple in construction, very easy to repair and is low in price, its use has spread widely, especially in agricultural districts. The life span of this type of heater is about ten years [114].

A more recent type of solar water heater, which is an improvement over that in Fig. 95, has a larger capacity and is usually placed on an inclined roof surface facing south (Fig. 96). The southern face of the heater box is made of wire netting and a curved reflecting surface made of aluminum foil is placed in front of it. The inside face of the heater box is covered by black vinyl membrane to hold water; reflected rays passing through the wire netting to the vinyl membrane heat the water. With its reflector the new open-type solar water heater thus uses more solar energy than the ordinary open-type heater. The area of this water heater is 0.9 m x 2.0 m and the capacity is about 180 liters.

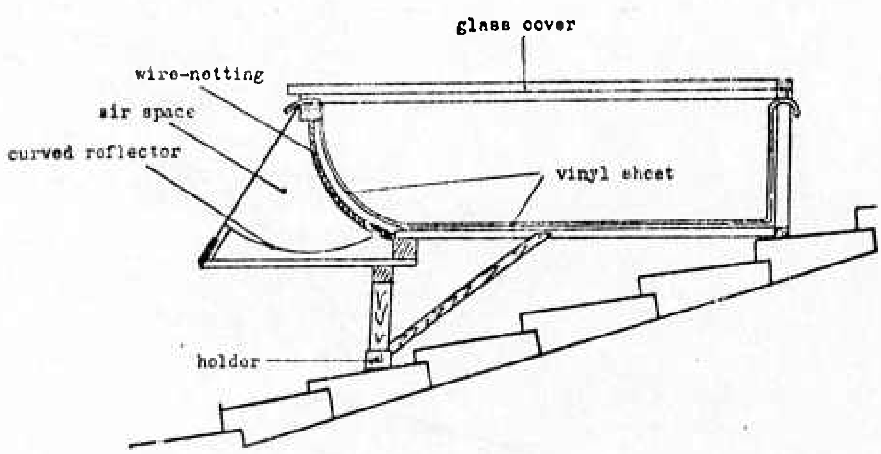


Fig. 96. Solar water heater of 180 liters capacity, Japan [114].

Another open-type solar water heater, produced by a different firm in Tokyo, is on the same in principle as the one shown in Fig. 95 but differs in details. It is constructed of wood and plastic without

using any metallic part. The inside face of the heater box, the dimensions of which are 0.74 m x 2.7 m x 0.15 m, is covered by a polyethylene film about 1 mm thick. Water is let into box to a depth of 0.11 m, and it is covered by a thin transparent polyethylene film above the water surface. The life span of this solar water heater is considered to be very long, owing to the durability of the polyethylene film. All the material is supplied in one package and is very easy to assemble with simple tools (Fig. 97).

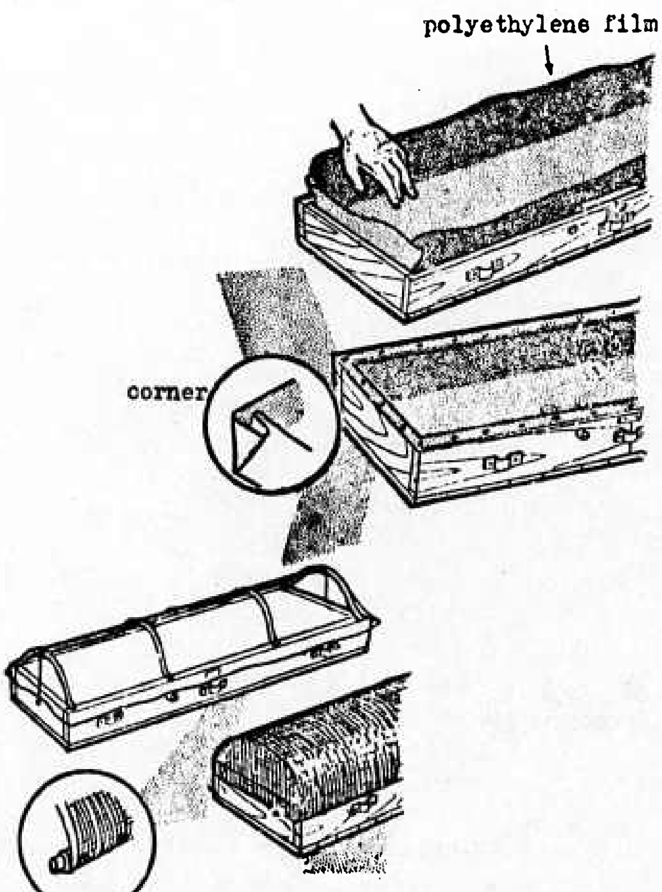


Fig. 97. Open-type solar water heater, Japan [114].

A simple closed-membrane solar water heater made of vinyl film in the form of a water pillow appeared as early as 1955, but at that time solar water heaters were not yet appreciated, so that it was not much used and disappeared for a time. However, now that solar water heaters have reappeared and become more popular, more than half of them now in use in Japan are of this type, due mainly to their low price.

The standard size of the closed-membrane heater is 0.9 m in width, 1.8 m in length and 0.12 m in depth; it has the shape of a water pillow, and holds about 200 liters of water. Both smaller and larger types than this are also used. Usually, the bottom surface is made of black vinyl membrane and the top surface of transparent vinyl membrane: alternatively both the bottom and upper surfaces may be of black vinyl membrane. The heat-absorbing effect is approximately the same in both cases, the former being somewhat superior. In the summer season, from April to October, it can be used without covering (Fig. 98), but may be used in both summer and winter if it is covered by glass plate or transparent vinyl membrane (Fig. 99).

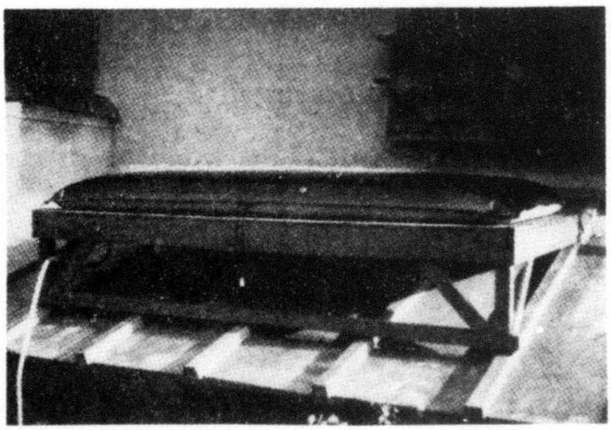

Fig. 98. Closed-membrane solar water heater without covering, Japan [114].

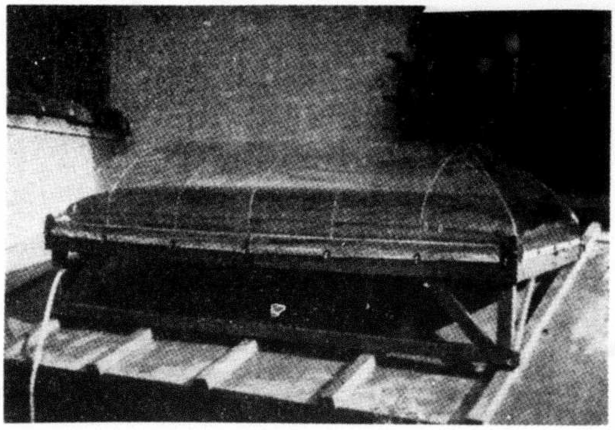

Fig. 99. Closed-membrane solar water heater with covering (glass plate or transparent vinyl), Japan [114].

The actual appearance of this type of solar water heater as a roof top installation is shown in Fig. 100.

Open- and closed-membrane type heaters must be placed horizontally, with the result that the heating effect in winter is very weak owing to solar declination in this season. By contrast, the closed-type heater is constructed so as to incline the heat receiving surface to the south to receive the strong sun rays. If this type were made of thin flat sheet metal, the lower part of the heater surface would expand and break the glass plate which covers the heater surface. For this reason, the closed-type heater is usually made of pipes with a diameter of about 0.12 m. One popular closed-type heater of simple construction (Fig. 101) is made of six circular

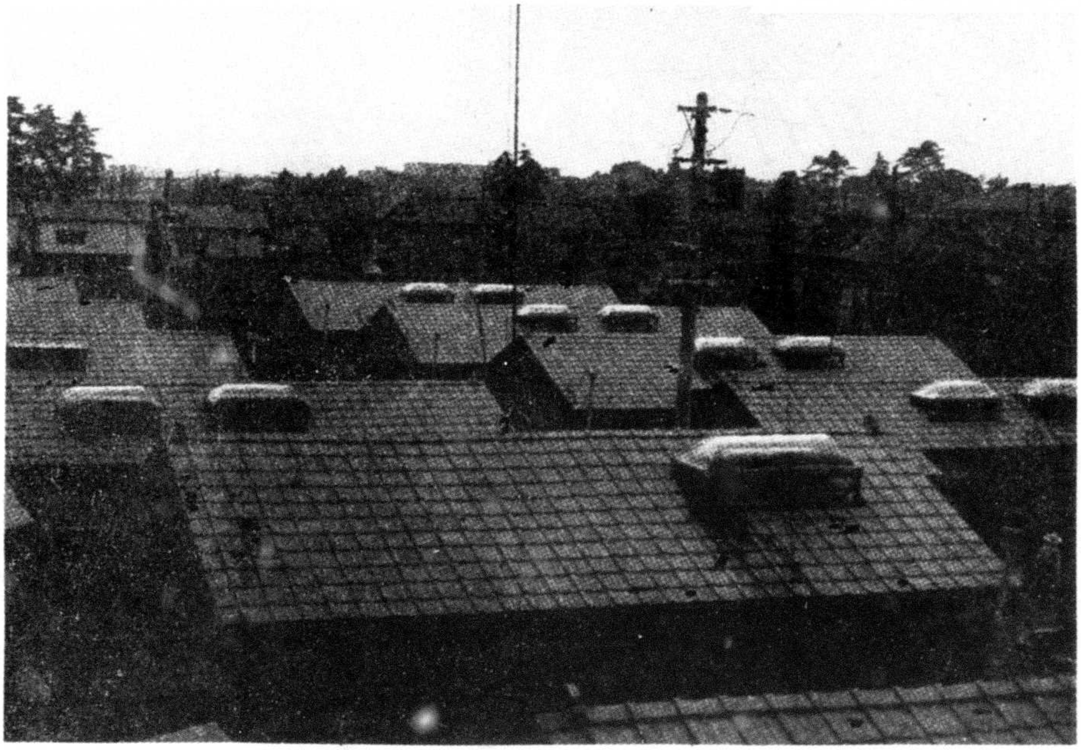

Fig. 100. Closed-membrane solar water heaters with covering, Japan [114].

pipes of thin aluminum or copper sheet, with a diameter of 0.12 m and a length of 1.1 m, and arranged in a wooden box (0.9 x 1.2 x 0.20 m). The lower parts of the pipes are connected to city water through a valve, and a small vent-pipe is attached to the upper part of each pipe to provide for washing of the glass surface when water fills the pipes in the morning. As the quantity of water for one box is about 80 liters, two or three boxes are jointly used for a domestic bath.

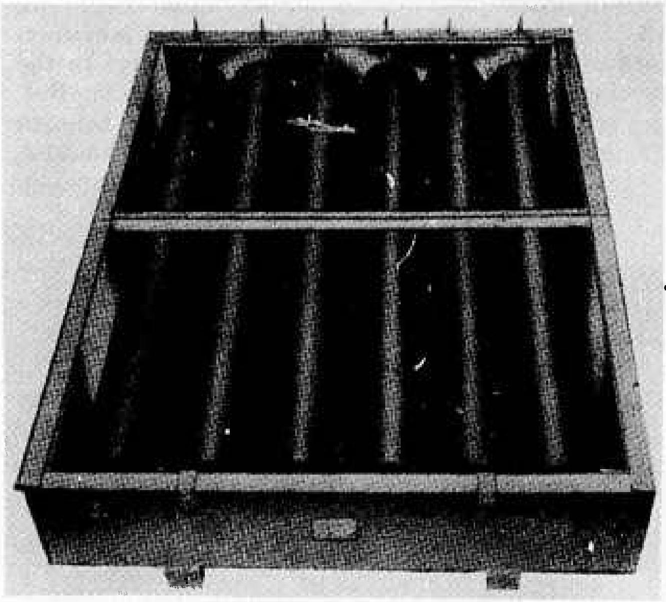

Fig. 101. Closed-type heater of simple construction, 80 liters capacity, Japan [114].

A modification of the above heater is achieved by adding a long pipe of small diameter in the lower part of heater (Fig. 102). This type is suited for washstands with intermittent low-volume hot water demand.

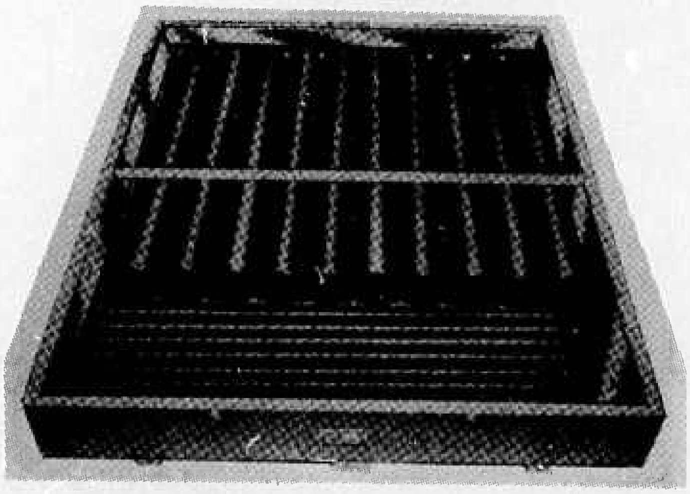

Fig. 102. Close-type solar water heater, Japan, [114].

These heaters can also be combined according to a given required daily volume of hot water (Fig. 103).

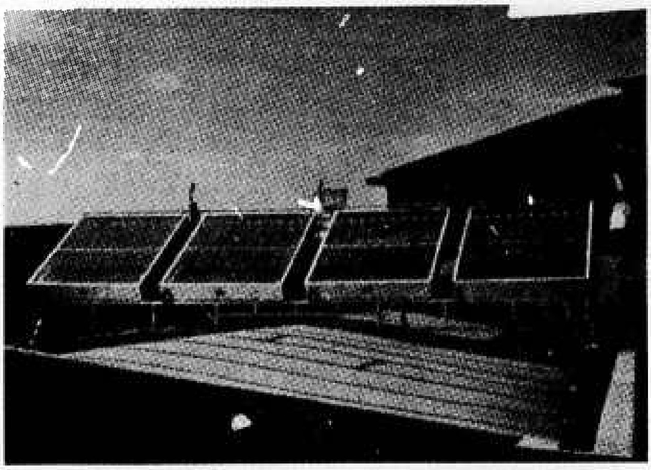

Fig. 103. Larger type solar water heater composed of four units, Japan [114].

Aluminum pipes are subject to corrosion, which can be avoided by using copper pipes. However, as the price of copper in Japan is relatively high, glass or plastic pipes have been used in closed-type solar water heaters of recent make.

A special closed-type heater made of two galvanized iron plates of ripple form and soldered to each other, with plastic film as coating for the iron plate, is illustrated in Fig. 104. This heater has a comparatively low cost; its dimensions are 0.915 x 1.85 x 0.23 m and it holds 175 liters of water, with a life span of about 10 years.

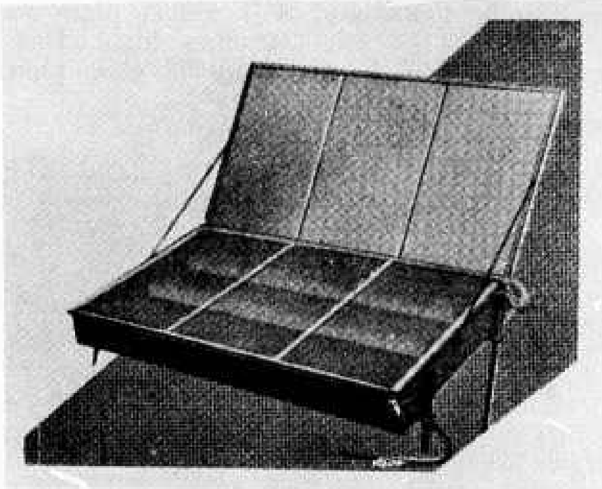

Fig. 104. Closed-type solar water heater with plastic-coated galvanized iron plates, Japan [114].

The closed-type heaters do not have any tank and connecting pipe, hence have a minimum surface area and are probably most effective in the heating period until about 2:30 or 3:00 p.m. Here the whole mass of hot water is contained beneath the glass plate, so the water is subject to reradiation in the evening. An intermediate insulated storage tank may be installed to minimize this loss.

Japanese scientists have designed and tested natural circulation (thermosiphon) type solar water heaters. This type is not commonly used as yet, owing among other reasons to the high price and the necessity to place the hot water tank on the roof. One natural circulation type heater (Fig. 105) has been designed with the hope of being simpler, cheaper, and suitable for common use.

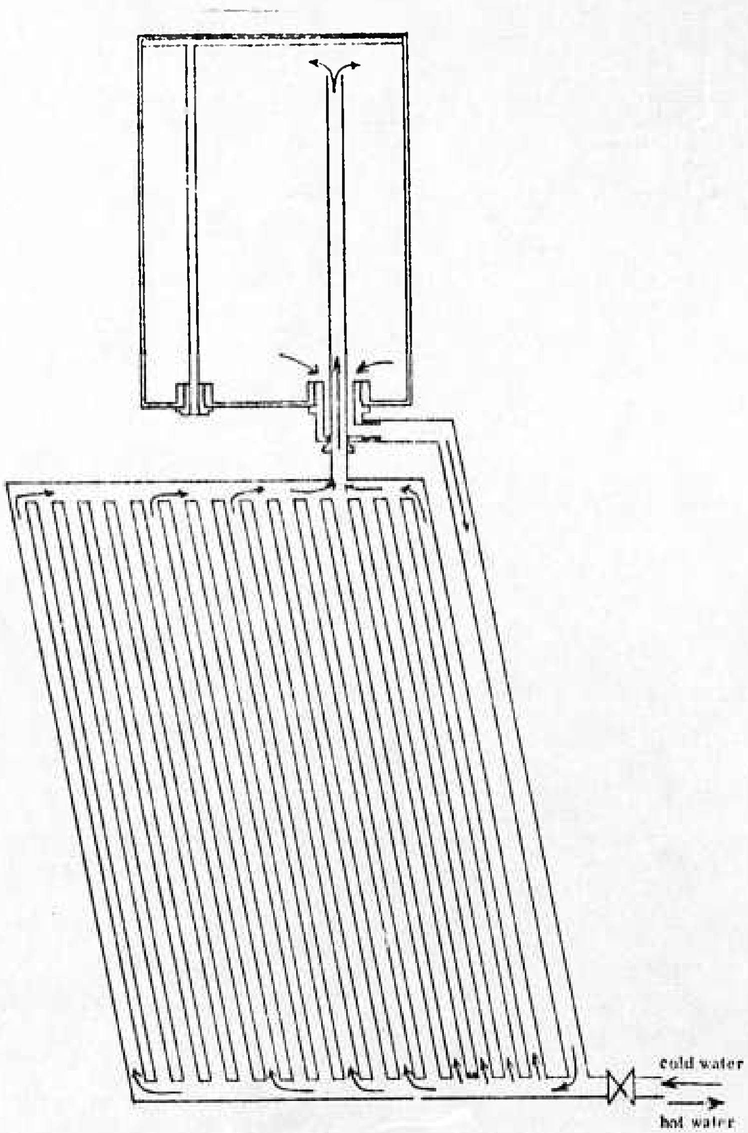


Fig. 106. Schematic of natural circulation (thermosiphon) type solar water heater, Japan [114].

Figures 106 and 107 show two versions of this solar water heater, a large and a small one. The heat-receiving area of the large one is 1.2 m x 2.7 m, and that of the small one, 1.2 m x 1.8 m. The water capacities

of both are about the same; the life span is judged to be about 15 years. From these conditions, it seems likely that the use of the natural-circulation solar water heater will spread to some extent for domestic use in the future.

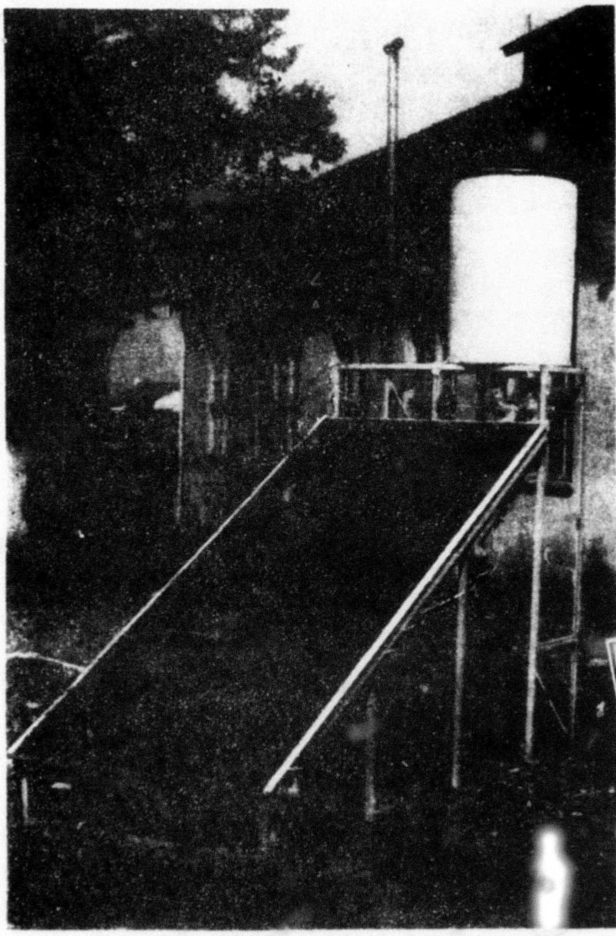

Fig. 106. Large size natural circulation (thermosiphon) type solar water heater, Japan [114].

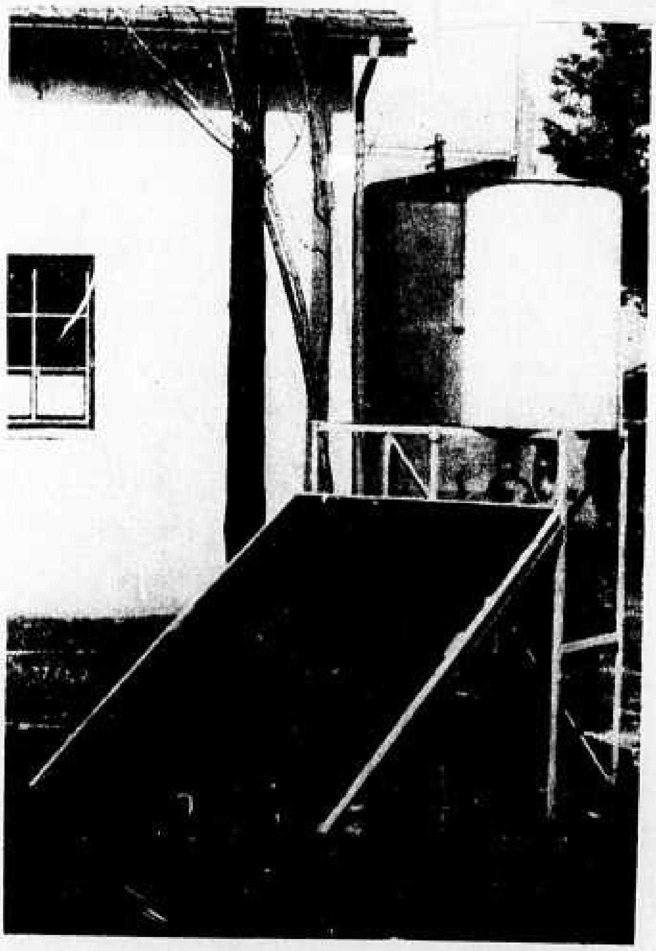

Fig. 107. Small size natural circulation (thermosiphon) type solar water heater, Japan [114].

Because there are many public baths there is a wide possibility of using solar water heaters of larger size in Japan. For this purpose, Japanese scientists constructed and tested a once-through type heater with a heat-receiving area of 66 $m^2$ at one of the dormitories of Keio University. The main purpose of this heater is to supply hot bath water for more than 100 students (Fig. 108).

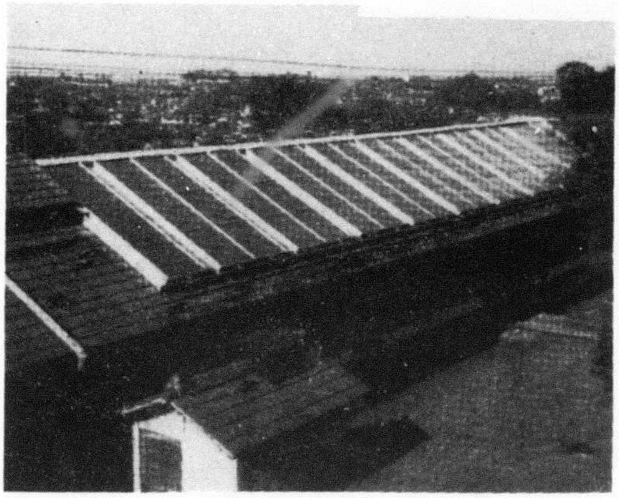

Fig. 108. Once-through type solar water heater of Keio University, Japan [114].

It was not practicable to use the thermosiphon type heater in this case because it was difficult to place a large water tank on the roof; the once-through type heater was therefore adopted. In this type, the cold water passes through the heating pipe only once, flowing out as hot water which is usually stored in a hot water tank. The heating pipes are of iron having an outer diameter of 20 mm, a thickness of 1.6 mm and a length of 4 m. Twenty groups of pipes were adopted, each group composed of 23 pipes arranged with a pitch distance of 35 mm. The inside and outside surface of the pipes was galvanized after the group of pipes was welded in one block. The pipes are well insulated except for the upper-side surface which is covered by glass plates (Fig. 109).


Fig. 109. Schematic of heating pipes for Japanese once-through type solar water heater; dimensions in meters [114].

This heater was designed to supply 7,000 liters of hot water per day at a temperature of 50° C, except in winter. After tests of several seasons, it was found that the desired results were nearly obtained. The life span of this solar water heater is rated at about 15 years. Conceivably, the once-through type solar waterheater of this large size will become widely used in Japan, and a large amount of fuel will be saved [114].

## USSR

In the Soviet Union, various types of solar water heaters have been designed and built using the same principles applied in other countries [116]. Water heaters of numerous sizes have been developed and used in

Tashkent, Askhkabad, Tbilisi, and other locales in Soviet Central Asia. The most ambitious is a large solar water heater in Tashkent, which has a capacity of 500 liters of hot water daily [97].

The Lenin State University in Tashkent has designed and tested a coil-type solar water heater for showers in construction camps, summer cottages, hospitals, and apartments (Fig. 110).

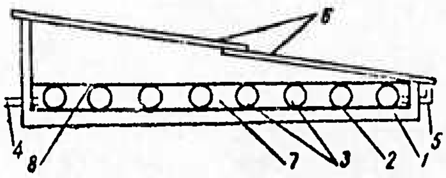


Fig. 110. Cross section of coil-type solar water heater, Tashkent [97].

1- reinforced concrete tank; 2- water-proofing; 3- coils; 4- drain; 5- overflow; 6- glass; 7- water; 8- oil film.

The glass that protects the tank from dust and loss of heat is supported on wood laths or small angle irons tilted slightly ($2-3^{\circ}$) towards the south. The glass can be cleaned with water from the coil. Tube (4) is used to drain the tank for cleaning purposes; tube (5) serves as an overflow.

The hot water (Fig. 111) is collected in an insulated tank (1), to which shower heads (2) are connected. The line connecting the outlet of the coil with tank (1) includes a sleeve (3) for a thermometer (4) used to

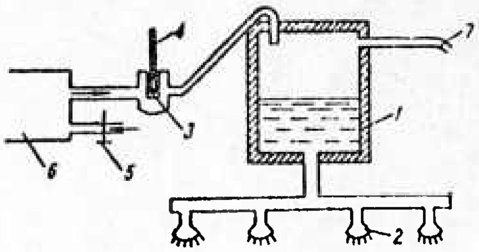


Fig. 111. Schematic of solar coil-type water heater, USSR [116].

measure the temperature of the water, which is regulated by varying the rate of flow through the coil by means of the valve (5). This valve is connected to the water mains or the storage tank of the heater (6). The hot water tank is also provided with an overflow (7).

Among several types of solar water heaters, this type is the cheapest and simplest to build and to operate [116].

Recently, an industrial type solar water heater was put in operation to supply hot water for the workshop showers of the Charvak hydroelectric power station on the Chirchik river, Uzbek SSR (Fig. 112). This installation has an irradiation area of 80 $m^2$ and a capacity of 5 tons of hot water daily at 60-70° C temperature. It is planned that parts of this installation, besides providing hot water, will operate a thermal semiconductor pump for air conditioning and heating of an administration building.

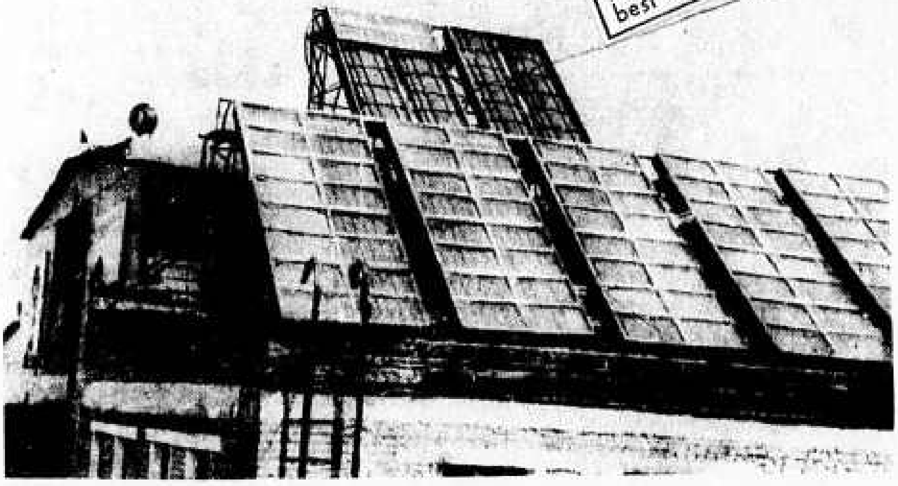



Fig. 112. General view of an installation in the Uzbek SSR. [117].

The hot-box solar water heating units consist of wooden frames 5.05 x 2.27 x 0.2 m in size. On their inside thermal insulation are coils covered with double glass panes. The whole installation consists of two levels: 2 upper and 6 lower sections. Each level can operate separately and feed the same tank with hot water. It is planned, however, to have two tanks, each 2.5 $m^3$ capacity, for each level.

Experimenting with this installation, Soviet scientists concluded that from a 1 $m^2$ solar absorber about 90 liters of hot water can be obtained at temperatures ranging between 55 and 60° C. Even during cloudy or partially cloudy days, this installation has produced about 60-70 liters/$m^2$ hot water daily at 40-50° C [26, 117].

The Physicotechnical Institute of the Turkmen Academy of Sciences in 1970 designed and tested a flat plate absorber (Fig. 113)

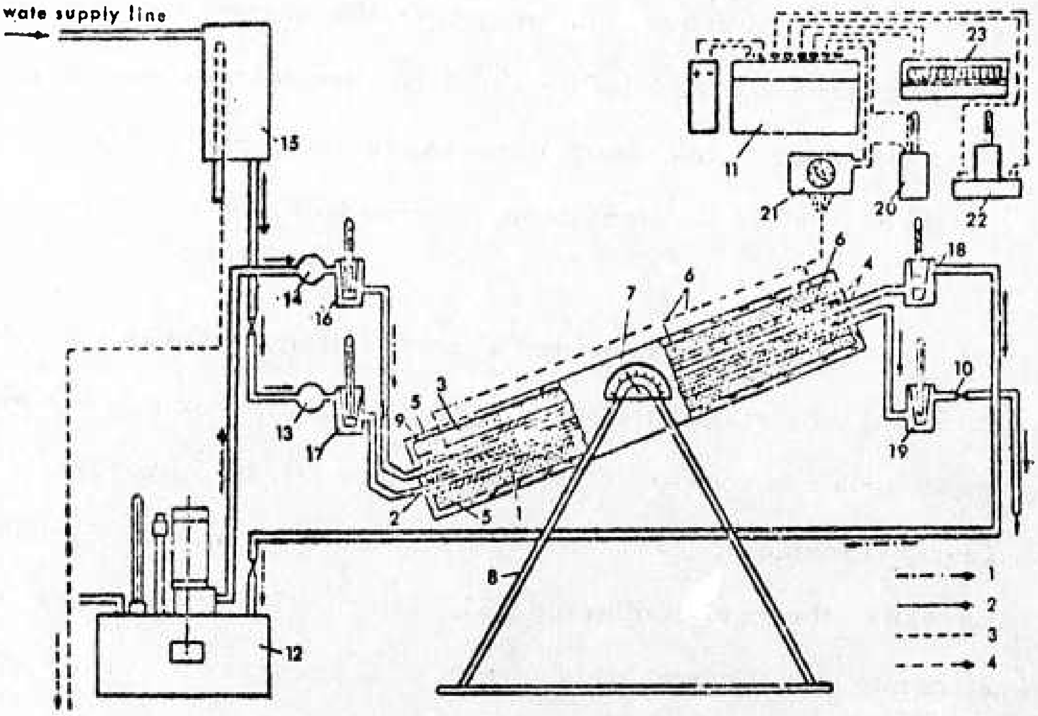


Fig. 113. Schematic of solar water heater flat plate absorber, USSR [118].

1 - hot water; 2 - warm water; 3 - thermocouple; 4 - overflow.

to determine the heat irradiation coefficient at various angles of inclination (0-180$^{\circ}$) of the absorber, and consequently the effect on total output of hot water.

This absorber is made of three stainless steel plates (1, 2, & 3) with 1000 x 250 x 3 mm dimensions and separated by 18 mm of thick rubber packing (4). Water is fed into the two channels formed by the three plates: the upper channel with hot water, and lower channel with cold water. To provide uniform overflow of the absorber, both upper and lower channels have 4 inflow and 4 outflow nozzles spaced at equal distances. Heat exchange temperature is measured by copper-constantan thermocouple (6) through slots (1.5 mm deep, 1 mm wide) on the middle plate (2).

The assembled absorber is installed in a wooden box (9) mounted on a stand (8) rotatable on a horizontal axis. The swinging angle of the absorber is measured by a protractor (7); the absorber is enclosed in a thermal insulator (5). Cold water is fed from a tank (15) under constant pressure through a collector (13). Circulation of hot water is regulated by a thermostat (12) operating with 0.1° C accuracy. Outflow of hot water is controlled by a regulatory valve (10), and the thermocouple emf is measured by potentiometer (11). Hot water flow, circulating in the upper channel through a thermostat, is kept at 350-400 kg/h. The temperature differences of hot water at inlets and outlets ranges between 5 and 9° C. With this model several tests have been conducted with absorber at 0°, 38°, 90° and 180° angles. (Items 14 and 16-23 of Fig. 113 are not identified) [118].

In conclusion, solar water heaters fitted with the low-temperature flat plate collector are used in order to reduce fuel costs. In regions where solar radiation is particularly intense and the climate appropriate, water is sun-heated during most days of the year. The need for auxiliary heating on overcast days, resulting in increased total cost, raises the problem of the economic feasibility of the system. Where conventional sources of heating are available, the combination of solar and auxiliary heating must be capable of competing economically with other systems. Among the factors governing the actual cost of solar heating, the expenses for auxiliary heating are thus of the greatest importance.

In order to estimate the essential proportion of auxiliary heating, local climatic conditions and their influence on the efficiency of the solar heater must be examined. With such data, it will be possible to calculate the minimum amount of auxiliary heating required to provide for year-round hot water consumption.

There appears to be a promising future for solar water heating. A great number of solar water heaters are already in use in some countries, and the number is still increasing rapidly. Technological improvements are being made, and costs are gradually being lowered. Although some problems remain to be solved, the facts indicate that the use of solar water heaters in underdeveloped countries will become popular [115].

C. Space Heating, Air Conditioning and Refrigeration.

1. Heating

One of the world's largest uses of energy is for space heating. Estimates of the proportion of the world energy consumption for this purpose lie in the range of 20 to 30 percent of the total for all uses. It is logical, therefore, that considerable effort is being devoted to the development of solar energy for this particular application.

For example, the heating of buildings in the United States requires one-fourth of all the fuel consumed in this country. Maintenance of winter comfort thus requires the annual consumption of coal, oil, and gas having a heating value of roughly 10,000 trillion Btu. This great quantity of heat is actually used at very modest temperatures, only 21 to 32$^{\circ}$ C. In a sense, this is a wasteful use of these concentrated energy sources which are capable of delivering heat at far higher temperatures. Simple equipment can be employed in the capture of solar energy at temperatures well above these requirements, so the large quantity of energy used in space heating makes this application of solar energy highly attractive. Only a small fraction of total electric generation is employed for air conditioning. In the early 1960's residential air conditioning required something less than 1 percent of total electric output. However, this use is growing very rapidly, and the electrical demand resulting from domestic air conditioning is approaching high levels in some regions. Here also the possibility of solar -operated cooling

units suggests itself both from the standpoint of an attractively large application and also from the energy-conservation point of view [17].

Just over 30 years ago the first solar-heated laboratory was constructed, and the first solar-heated dwelling was put into operation about 25 years ago. Since that time, about a dozen groups throughout the world have undertaken experimental work in this field, most of which has led to the design and construction of buildings heated by solar energy. These earlier efforts may be summarized, however, by observing that practically all of them showed that by use of several variations of the flat-plate solar collector, in combination with various types of thermal storage materials, a portion of the heat requirements of small buildings in the temperate zone could be conveniently supplied by solar energy. Also indicated in nearly all of the studies were the needs for short term thermal storage, auxiliary heat supply, and a reduction in the initial cost of the solar heating system [124].

There are several similarities between devices used in water and space heating and the two may in fact easily be combined. Basically, the system consists of circulating water or air through a black flat-plate collector in order to remove the heat, which is then carried into the house or into a storage tank containing water, crushed rocks or chemicals capable of absorbing heat and later released for useful purposes. The system may in some cases be operated in reverse in the summertime so that warm air or water is drawn through the collector or other part of the roof for moderate

cooling through night radiation. The various systems in operation differ in details. For solar space heating systems to be successful in under-developed regions, however, it may be prescribed that they should: require no auxiliary electricity; permit moderate and simple use of auxiliary fuel; permit moderately wide variations of interior temperature; and be low in initial cost. Unfortunately, few or none of these criteria appear to be met in the existing solar houses [3].

Any improvement in the present methods of storing solar energy will have wide applications and open the way to extensive and more economical use of the sun's heat. Space heating is one of the most important fields to offer the simplest direct use of solar energy, since only a relatively small increase in temperature is needed. Hence considerable attention has been given during the last several years to the importance of storing the sun's heat for later use in supplying vital heat when it is not so available. The storage problem for some localities may be for short periods only, i.e., storage during daytime and use during the night.

The designs tried so far include a flat-plate collector, a storage system, and a means of conveying heat from collector to storage. For reasons of economy, the collector is usually designed to act as the roof of the building, which brings up the problem of proper architectural design regarding favorable angle of roof tilt and the correct orientation. The major problem in the design of a storage system is the selection of

material in which the heat energy is to be stored, since it determines the capacity of the system. The materials tried can be divided into two broad types: those that store energy in the form of sensible heat, and those that undergo a change of state or physicochemical change at some temperature within the practical range of temperatures provided by the solar heat collector, varying between 90° and 120° F.

In the first category of materials, water and rock pebbles have been found to be the most practical storage materials. Thus, one cubic foot of water can store 62.5 Btu per °F rise in temperature, while one cubic foot of rock can store about 36 Btu per °F. If we assume an average temperature rise of 30° F, the heat storage capacity of 1 cubic foot of water comes to 1880 Btu and that of rock to about 1080 Btu [68].

The Department of Mechanical Engineering of the University of the West Indies, St. Augustine, Trinidad, recently designed and tested a two-pass solar air heater to determine its performance, considering the thermal losses from the solar collector surface. In an attempt to reduce the losses from the glass cover of the simple two-glass cover air heater, a unit was constructed in which provision was made for the air to pass between the glass panes before passing through the blackened metal collector (Fig. 114).

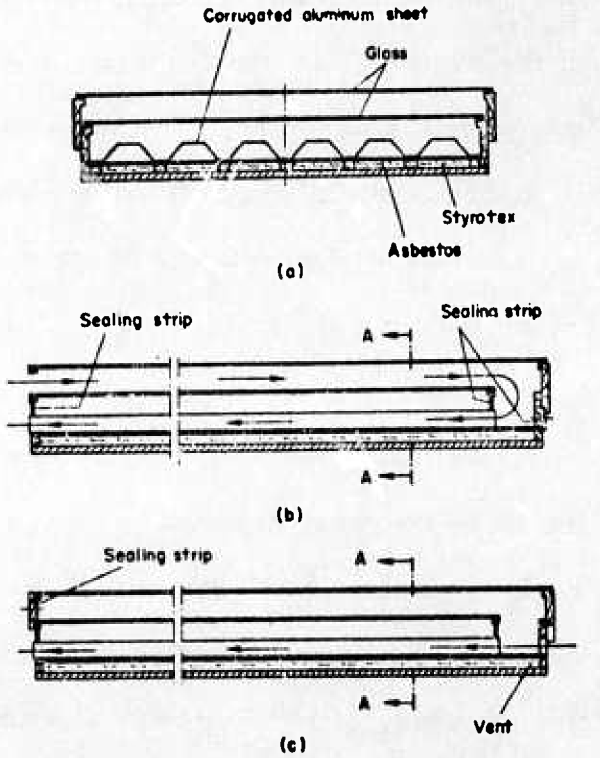


Fig. 114. Schematic of experimental heater, Trinidad. (a) section A-A, (b) double pass, and (c) single pass [122].

It was found that the outer glass cover temperatures under these conditions were significantly lower (4-10° F over the day) and much nearer atmospheric temperatures than when the collector was operated in the conventional single-pass manner. Consequently, efficiencies of 10-15 percent higher were obtained.

The metal element of the heater consists of a piece of corrugated (trapezoidal corrugations) aluminum sheet normally used for roofing, fastened to a sheet of galvanized iron. The element is mounted on the bottom of a wooden box with sheets of asbestos and styrotex between the metal and the wood. The lower glass pane is fitted in such a manner that it does not quite cover the whole length of the box. The top glass cover is carried on a wooden frame designed to fit over the first one, so that the distance between the two glass panes could be varied. The glass used was ordinary window glass. The outlet of the metal element is connected with suitable ducting and piping to the suction end of a blower with a standard nozzle orifice in the line.

The two-pass variant thus results in significant improvement in the performance of the collector, at no increase in the cost of the unit [122].

The principal components of a solar heating system for a building are closely analogous to those of a conventional system, with one additional component. In conventional design, there is the energy-conversion or heat-transfer unit commonly known as the furnace, the function of which is the transfer of chemical energy in the fuel to a medium such as air, water, or steam. In most systems, there is also a pump or blower to circulate the heated fluid to and from the space to be heated. Usually there are pipes or ducts through which the heated fluid or air is circulated and registers or radiators from which heat is transferred to the rooms. Thermostats and other control elements regulate the supply of fuel and the movement of the heat-transfer medium as required.

In a solar heating system, one of the several types of solar collectors serves the purpose of a heat exchanger in which solar energy is employed for heating the transport medium, usually air or water. This solar heating system may then supply heated fluids or air through pipes or ducts being moved by fans, pumps, or other equipment.

Although a conventional system usually employs only one unit for circulating the heating medium, a solar heating system may require two or more pumps or blowers for the various requirements of moving fluid or air from collector to storage, storage to heated space, and from heated space to the other units in the system. Ducts or piping between the heated space and the system components may be similar to identical to those involved in conventional systems, and the ultimate medium for room heating may also be the same.

There are numerous factors in the design of a heat-storage system. These include the storage medium, operating temperature range, heat-storage capacity, transport material, means for transferring heat from transport medium to storage and from storage to the medium of heat transport to the heated space.

The use of crushed rock or gravel for heat storage is convenient in the combination of a solar air heater and a hot-air heating system. With a heat capacity only about one-fifth that of water, five times

as much gravel needs to be employed for storage of the same quantity of heat between the same extremes of temperature. Storage of 1 million Btu of heat over a $37^{\circ}$ C temperature range would require about 25 tons of loose rock, which would occupy a bin about 8 ft on a side.

An important factor in the storage of heat in a gravel bed is sufficient void space to permit free circulation of air through the mass. Uniformly sized rock facilitates air movement at moderate pressure requirements, and since heat transfer rate requirements are very low, comparatively large-diameter rock (2 to 3 in) can be employed without efficiency loss. The rock really serves three purposes: It is a heat exchanger, transferring heat from the hot-air stream to storage; it is the storage medium itself; and it is a heat exchanger, transferring heat from storage to the air stream circulating through the house. It is entirely analogous to the regenerative heat-transfer units employed in conjunction with blast furnaces and open-hearth furnaces.

Glauber salt ($Na_2SO_4 \cdot 10H_2O$) and sodium phosphate dodecahydrate ($Na_2HPO_4 \cdot 12H_2O$) melt and dissolve in their own water of crystallization at $32^{\circ}$ and $36^{\circ}$ C, respectively. The latent heat effect on these processes is 104 and 114 Btu/lb, respectively. When heated by a medium above this temperature, the salts melt and absorb these energy quantities; when surrounded with a medium cooler than about $30^{\circ}$, the salts recrystallize and give up the heat of crystallization to the cooling medium.

Small containers of the salt can be stacked or otherwise packed in bins or closets through which solar-heated air is circulated, thereby storing heat for subsequent use [17].

The use of materials that undergo physicochemical changes has been largely proposed for the purpose of reducing storage space. In early pioneering work on solar house heating, Maria Telkes introduced the idea of using a hydrated salt, such as the Glauber's salt already mentioned, which on heating melts in its own water of crystallization. This appeared to be a very satisfactory solution of the storage problem until it was found that these materials can be very temperamental in their behavior, and in the absence of crystal nuclei or stirring, considerable supercooling could take place before the material started to recrystallize and yield its latent heat. The heat-of-fusion materials were therefore discarded by some subsequent designers of solar heated houses who turned instead to bulky but more dependable materials, like water or pebbles.

Although largely abandoned for this reason, the salt substances nevertheless offer means both of reducing storage space and of heat storage at higher temperatures. With this in mind, Martin Goldstein of the National Physics Laboratory of Israel undertook a survey of materials that could possibly be used. His aim was to find chemical systems which will give the greatest storage of heat per unit mass or unit volume, since heat losses and insulation costs will depend on the volume of the enclosure, rather than on the mass of the substance contained in it [68].

After surveying many groups of substances, Goldstein, classified them roughly as follows:

- o inorganic and organic substances with large heats of fusion, having melting points within the temperature range of $30^{o}$ to $200^{o}$ C,
- o eutectic mixtures of inorganic salts,
- o change-of-phase class of substances,
- o solid-to-solid transitions,
- o heats of solutions,
- o heats of vaporization, and
- o storage by chemical reaction in solution.

Goldstein's study, based on purely thermodynamic grounds, suggested the usefulness of more detailed investigation of some more promising lines, such as the vaporization process.

In temperate and tropical climates, energy storage could be obtained for a much longer period. The cheapest form of energy storage in this case is as sensible heat in rocks or water, and the capacity needed for long-term storage, i.e., summer heat for winter use, would not require more than a small percentage of the volume of the space being heated or cooled. Even less space would be needed for short-term storage; this space can be further reduced if chemical storage methods are applied, though at a higher cost. The efficiency of storage is based on two superimposed duty cycles, i.e., the daily variations in temperature on top of the seasonal

variations from summer to winter. In general, for long storage at least 50 percent of the energy put into storage must be available some three months later.

Storage capacity is inversely related to collector capacity, but if storage efficiency is high then the collector capacity (i.e. area) can be reduced. In addition, the rate of storage or withdrawal is not considered of importance unless the storage is done as heat of fusion.

Allcut and Hooper of the University of Toronto have examined the special problems of solar energy utilization in Canada. In the higher latitudes of northern Canada, conditions for solar energy use are limited as the mean annual total of bright sunshine is about 1400 to 1600 hours, and in December there may be less than 25 hours of sunshine. The region of southern Ontario has been examined in some detail; here it was concluded that if the heating system is to be entirely independent of auxiliary sources, it would be essential to have a long-term storage system to carry over the heat collected during summer. Otherwise, the collector area would have to be very large, and would exceed the projected south-facing area of a normal house. After analyzing several designs, Allcut and Hooper concluded that a solar heated house, fitted with a panel heating system which could effectively use heat at a temperature of 26.7° C, would be economically feasible if a large reservoir with heat storage at 62.8° C and with only limited amount of insulation could be provided [68].

An important component in the solar heating system is the furnace or auxiliary heating unit, although this would ordinarily be a conventional item of a standard heating system.

There are several ways in which the furnace can be used to supplement solar heat. The objective is to have auxiliary heat available whenever needed, but to use the minimum amount of fuel consistent with human comfort in the building. A design involving completely separate water piping or duct-work systems from a furnace is not necessary and involves excessive installation cost. Hence, the furnace should be arranged to heat the same fluid and distribute it through the same channels employed for solar heat. One of the simplest designs is a hot-air system in which air from the solar collector or storage can be passed through the furnace, if necessary, before distribution to the rooms. This arrangement permits maximum utilization of solar heat, fuel being used only when air temperatures from the solar system are inadequate for carrying the heating load. In one design, air from the solar system always passes through the furnace, fuel being used only when required.

In another arrangement, a bypass and automatic dampers divert part or all of the air through the furnace when needed. The same sort of combination may be provided in a hot-water heating system. These designs have the advantages of simplicity and the avoidance of auxiliary heat use except

when actually required. Such systems also respond rapidly to heating demands, particularly when atmospheric temperatures are subject to rapid change. They have the disadvantage of creating maximum demands on natural gas or electric networks simultaneously with maximum demands elsewhere in the area, and do not permit economies which might be obtainable by use of off-peak energy.

The heat pump presents a number of special requirements when used in conjunction with a solar heating system. The heat pump is a refrigeration system which utilizes electric energy for operation of the compressor. When cooling is desired, it is operated just as a conventional compression-type air-conditioning unit. Heat is withdrawn from the living space and rejected at higher temperatures outdoors to the atmosphere. In winter, reversal of refrigerant or air flows permits the supply of heat from the cold atmosphere to the refrigerant and the increase of this temperature by compression so that heat is then delivered to the rooms at higher temperature.

Automatic control of heating and cooling systems is an essential design feature. When augmented by solar collector and storage equipment, with their fluctuating output, these systems have a complexity and variability which can be controlled only by a complete automatic assembly carefully designed for the application being made. In addition to

requiring the conventional thermostats which act to start and stop fuel supply, air circulation, hot-water circulation, and other operations in a house, a solar heating system usually must have thermostats in the solar collector and the heat-storage unit. The collector thermostat has the function of controlling the motor which drives the pump or blower that circulates the heat-collecting medium from solar collector to storage (or to the living space). This thermostat senses solar radiation and is set so that the circulating motor will be in operation whenever heated fluid can be delivered from the collector at a useful temperature.

In addition, the storage thermostat serves to actuate a motorized fuel-supply valve or fuel pump in the auxiliary furnace, as well as to control an auxiliary heater, in conjunction with a house thermostat, in supplying fuel to a furnace whenever the house requires heat from storage which is colder than a present value [17].

It would appear that for most applications, the cheapest solar heating system will be one in which entire dependence is not placed on storage alone but in which provision is made for auxiliary heat. If such a compromise could be accepted, then the cost of storage could be brought within economic limits.

Impressive work has been done on solar house heating in the United States and other countries [68]. The status of these solar heating

developments will be outlined in very general form, with respect to the design and operation of several recently completed solar heated structures. However, this application should be considered as in an early experimental stage, since to date only a few dozen solar-heated structures have actually been built and tested. In this study, a solar-heated structure may be defined as a building in which a solar energy collector in combination with a heat-storage unit provides a substantial portion of the heat required in the structure. Since there are substantial differences in the design and operating characteristics of practically all the existing solar heating systems, brief descriptions of each are presented here. Where the data are available, performance is given in brief. Several other structures originally provided with solar heating systems, although they are no longer in service, are also described because the designs are distinct from those now operating.

In 1958, a solar-heated residence was completed at Lexington, Mass.by MIT. The heating system comprises a solar water heater mounted on a large sloping roof, hot-water storage, oil-fired auxiliary furnace, and hot-air supply to the house rooms. General features of the house and heating system are shown in Figs. 115 and 116. The house has two floors of living space totaling 1450 $ft^2$. The south elevation is exclusively occupied by a 640 $ft^2$ solar collector in 60 panels, each 4 ft long and 32 in. wide. This portion of the roof is oriented at an angle of $60^{\circ}$ to the horizontal for ideal exposure to the winter sun. Solar energy is absorbed on a blackened aluminum sheet to which are fastened 3/8 in. copper tubes 5 in. apart. The absorbing

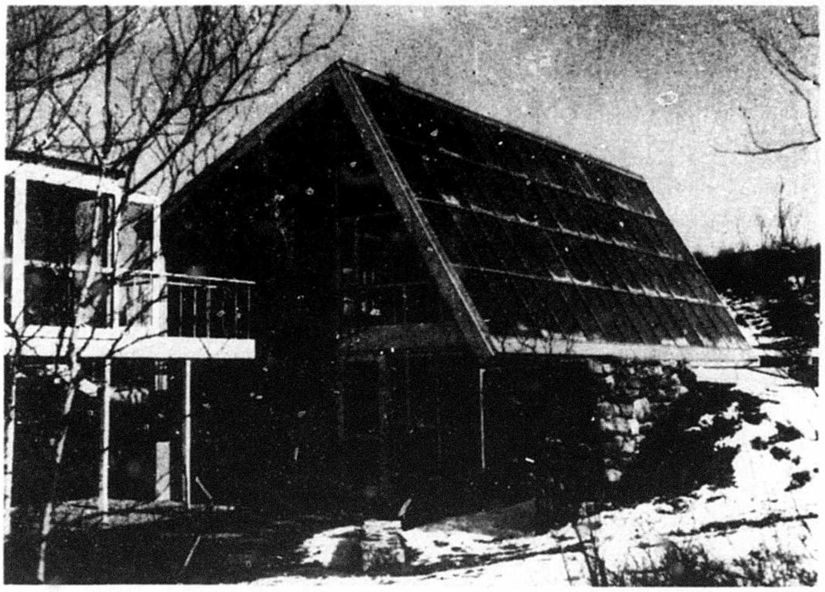

Fig. 115. Solar heated residence at Lexington, Mass. [17].

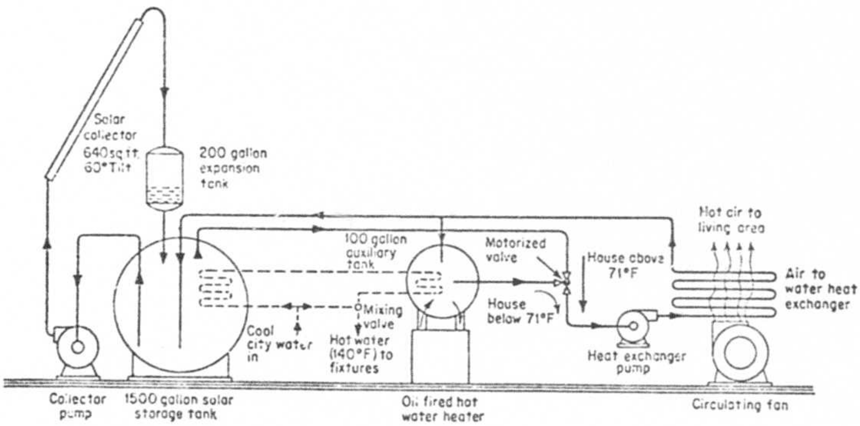


Fig. 116. Functional diagram of solar-heated house of Lexington [17].

surface is backed by glass-fiber insulation and covered by two layers of window glass spaced 3/4 in. apart. Heat storage is provided in a 1500-gal tank from which water is pumped to a heat exchanger for heating air circulated from the house by a fan. An oil-fired water heater provides a reserve of hot water (135 to 150° F) in a 275-gal tank. This tank is automatically called upon to deliver hot water to the heat exchanger whenever the temperature in the large storage tank is too low to provide adequate heat to the house. After passage through the heat exchanger, water returns to the large storage tank for reheating in the solar collector. Domestic hot water is provided by circulating it through coils in the large and small storage tanks.

A nine-room residence in Denver and its associated solar heating system were completed early in 1958. The house is of contemporary architectural style, flat-roofed, one-story (with partial basement), having 2050 $ft^2$ of living space on the main floor. The house was designed independently of its solar heating system, but the latter was incorporated into the plans in their final stages. This experimental project was directed by George O. G. Löf for the American-Saint Gobain Corporation (Fig. 117)

The solar collector is an air-heating type with the overlapped glass-plate construction. Two 300-$ft^2$ panels are mounted on the roof at a 45° angle. Each panel contains 20 sections, 6 ft long and 30 in wide.

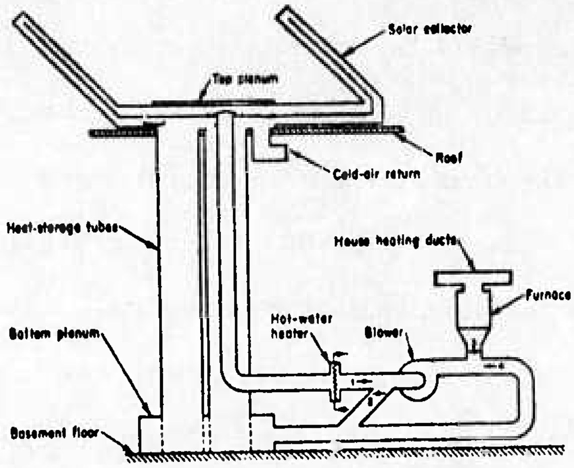


Fig. 117. Schematic of Denver solar heating system [17].

Recirculated air passes through two sections in series, once upward and once downward, into a manifold which connects all section exits. Hot air at temperatures up to a maximum of about 175° passes down to the basement, where it first gives up a small amount of heat to the house hot-water supply in a finned heat exchanger connected to an 80-gal water-storage tank by gravity circulation. The hot air then passes to the suction side of the blower thence either to the bottom of the storage unit or up through the furnace to the distribution system.

The heat storage unit consists of two cylinders of fiber board (standard forms for round concrete columns) filled with approximately 11 tons of 2 to 21/2-in. gravel. The rock column is 18 ft high, extending from the basement floor to the roof. Heat is transferred from air to rocks, the

cool air leaving the top of the gravel columns and returning to the solar collectors for reheating. Essentially complete heat transfer is obtained by the large surface area in the storage chambers.

When thermostats in the house call for heat, air is circulated to the rooms directly from the solar collector if the sun is adequate for actuating that particular circulation arrangement. Whenever the solar collector is not receiving solar radiation, the house thermostats cause two motorized dampers to shift their position, permitting the blower to draw air down through the heated storage chambers and force it through the furnace to the house distribution ducts. Cold-air ducts return air from the rooms to the top of the storage unit for reheating. Auxiliary heat is supplied to air in transit to the rooms by combustion of natural gas in a furnace through which the air passes. A thermostatic delay system supplies gas to the furnace only after air has been passing to the rooms for 10 to 15 min without satisfying the heating demand indicated by the thermostat setting.

A one-story office building having a floor area of 4300 $ft^2$ was completed in Albuquerque, New Mexico, in 1956 (Fig. 118 and 119).

The sloping south wall contains 700 $ft^2$ of solar collecting panels of the water-heating type. Solar radiation is absorbed on blackened aluminum collector plates containing integral tubing spaces. The collector

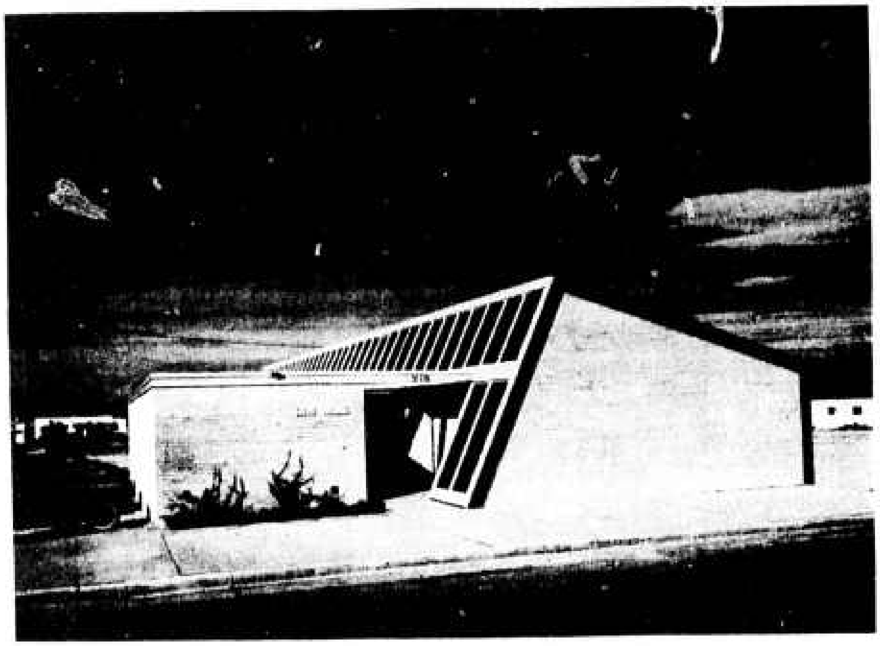

Fig. 118. Solar-heated office building, Albuquerque, N.M. [17].

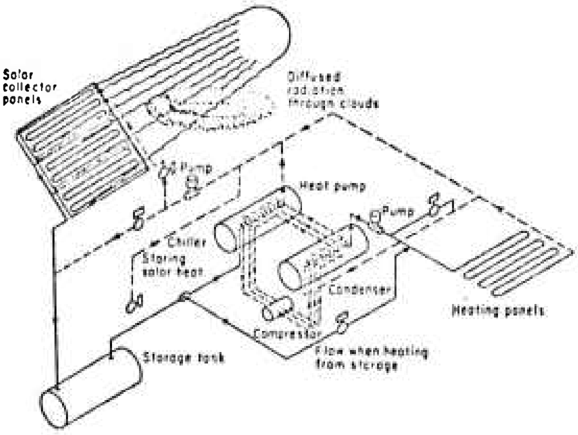


Fig. 119. Schematic diagram of solar heating with auxiliary heat pump, Albuquerque [17].

was subsequently modified by installing copper tubing in contact with the aluminum plate, thereby avoiding corrosion in the aluminum system. The collector is tilted $60^{\circ}$ from the horizontal and is glazed with one layer of common window glass.

Heat storage is provided in a 6000-gal insulated water tank installed underground. Heat is supplied to the building by circulating warm water from the storage tank to tubing in floor and ceiling panels at relatively modest temperatures of 95 to $110^{\circ}$ F. Auxiliary heat is furnished by a heat pump. Summer cooling is provided by a 7 1/2 ton heat pump operating in conventional manner with heat discard to the atmosphere in an evaporative cooling tower. An interesting supplementary feature is the use of the evaporative water cooler to provide chilled water for circulation through the panel coils whenever the cooling load is moderate.

The solar-heated laboratory at the University of Arizona, was completed in 1959 and tested during the winter of 1959-1960. The building is styled as a bungalow and used as a laboratory for solar energy research. It has 1600 $ft^2$ of floor area, is well insulated, and has 435 $ft^2$ of double windows. The heat requirement at the design temperature of $30^{\circ}$ F is 34,600 Btu/hr.

A unique feature of this system is the use of the solar collector not only as a heat receiver, but also as a heat radiator for cooling

purposes. This 1625-ft$^2$ unit covers the entire roof, and actually is the roofing as well as a heat exchanger. It is constructed of copper sheet with 120 integral parallel watertubes 5/16 in. in diameter and 5 in. apart and connected at their ends to hot and cold manifolds. The material for the collector surface is shipped flat in long coils, 16 in. wide, and the tubes are inflated hydraulically at the construction site. These pieces are joined together on the roof by means of cleats to form a continuous metal surface. No glazing is used above the metal plate, and, for aesthetic reasons, a dark green paint has been used rather than black.

The heat-storage tank contains approximately 4500 gal of water. This tank is divided into two sections by means of a horizontal insulating baffle so that water at two different temperatures can be stored simultaneously.

Auxiliary heat is supplied by means of a small heat pump of 1-1/2 hp. In a manner similar to that used in the Albuquerque building, hot water from the solar collector or from the "hot" section of the storage tank can be used to supply the heating requirements directly, when it is warm enough. At other times, it serves as the low-temperature heat supply to the heat pump, heat then being delivered to the building from the high-temperature side of the heat pump. Heat is transferred to the rooms by use of a continuous radiating ceiling constructed of the same type of material as that used on the roof. Water is circulated through 66 parallel tubes in 33 circuits.

The heating panel completely covers the ceiling of all rooms, having a total area of 1320 $ft^2$.

When operated as a cooler, water is pumped from the storage tank through the roof heat exchanger at night, radiating heat into the atmosphere. On a clear summer night, the large area of the unglazed unit permits discharge of up to 1/2 million Btu from water at about 70° F. On the following day, the cooled water is used directly in the ceiling panels for building cooling, or, if its temperature is too high, the heat pump chills it by transferring heat from it into the hotter, or condenser, section of the storage tank. This heat is dissipated the following night in the roof heat exchanger. Fig. 120 gives a schematic diagram of this installation (winter heating and summer cooling).

Thomason Solar Homes, Inc. of Washington, D.C., has for the last 13 years been designing and marketing several type of solar-heated houses. The first of these has a floor area of about 1500 $ft^2$ and a solar collector of 840 $ft^2$ located on the roof and sloping south wall. The heat-collecting surface is blackened corrugated sheet metal beneath one or two layers of plastic film and glass. Whenever the sun is shining, water is pumped from a 1600-gal storage tank to the top of the collector and allowed to run down on top of the corrugated surface to a gathering trough and back to storage. Maximum water temperatures are in the 125 to 135° F range.

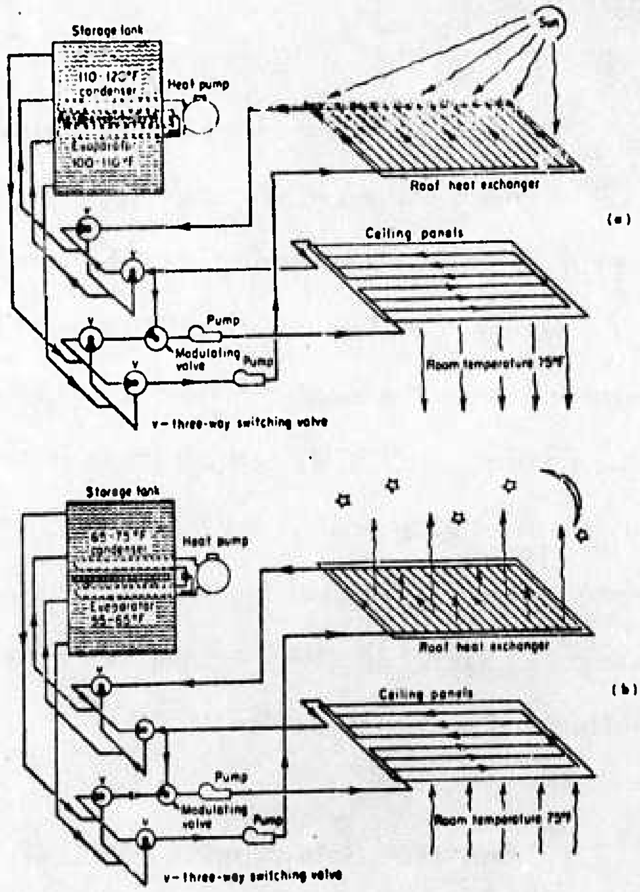


Fig. 120. Schematic diagrams of (a) winter heating and (b) summer cooling system in Solar Energy Laboratory, University of Arizona [17].

The water storage tank is surrounded by 50 tons of small rocks which are intended to provide additional thermal storage by conduction and convection transfer from the tank.

The house is heated by circulating air around the tank and through the rock-filled chamber to the rooms. When the available heat supply is not adequate, the storage system is bypassed, and an auxiliary oil furnace supplies heat to the air stream.

Cooling is also provided by use of day-night temperature difference. Daytime removal of heat from the rooms is effected by circulating house air through the previously cooled rock bin. Heat is then transferred to the tank of water, and the water is cooled at night by circulating it across a bare metal portion of the house roof [17].

The basic system is illustrated in Fig. 121 for winter use, and Fig. 122 for summer use.

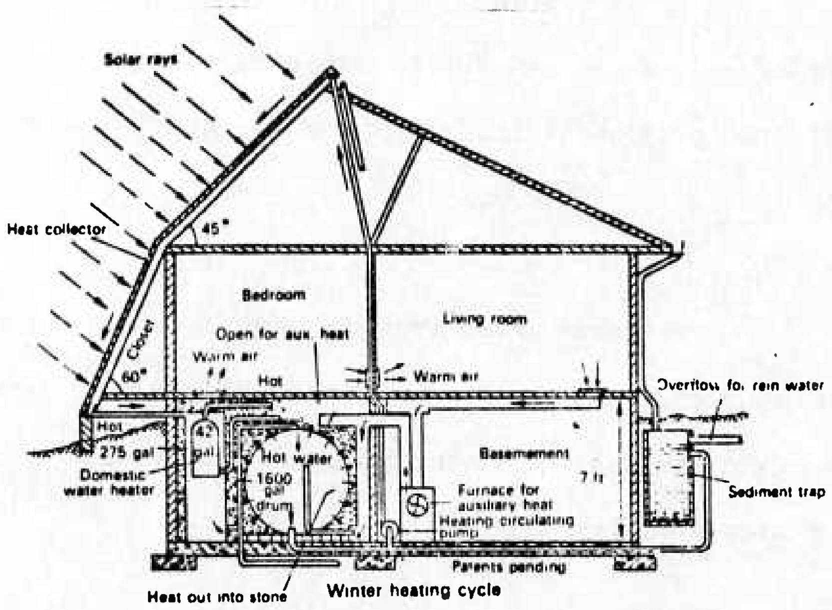


Fig. 121. Basic solar heating system during the winter heating season, Thomason Solar Homes, Washington, D.C. [120].

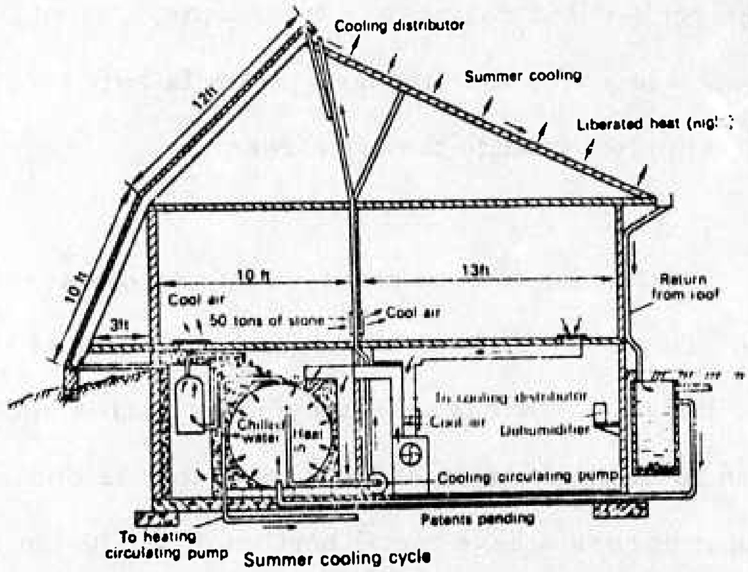


Fig. 122. The basic system used for cooling during summer, Thomason Solar Homes, Washington, D.C. [120].

This system has supplied most of the heat requirements despite half-cloudy weather and temperatures well below 0° C. In addition a substantial portion of the domestic water heating was achieved by solar heating.

Several other systems have been developed and tested by the Thomason firm. Advantages and disadvantages have been determined for each system and pertinent components. Following are some minor alterations for six later models:

o Solar house no. 2, built in 1960 - 1961, went through a number of changes. Cost for the original system was lowered, but the auxiliary heat cost ran slightly higher. An aluminum reflector was installed at the bottom of the solar heat collector to reflect additional sunlight onto the collector. The problem of summertime heat leakage from the solar heat collector into the closet space behind the collector was solved, keeping the closet cool.

o Solar house no. 3 was improved in architectural appearance. A minimum of glass breakage was achieved using low cost glazing. The heat collector was moved entirely up to the roof, permitting winter sunshine to enter the living room and a built-in swimming pool on the south side. In addition, improved air conditioning was installed.

o Solar house no. 4 has a new type of solar heat collector using asphalt shingles and a new type of low-cost "pancake" heat storage. Both were used in an A-frame house.

o Solar house no. 5, planned for a South Carolina firm, was never built owing to insufficient funds.

o Solar house no. 6 has been completed in Mexico. The house and the system were not constructed according to the designer's recommendation so the solar heating system does not provide the major

part of the heat load. Although Mexico City is quite far south (19° N. lat.), the temperature drops below freezing at times and can go into the low 20's.

o Solar house no. 7 is a new design, ("Sunny South Model")* (Fig. 123 and 124) using a rooftop pond from where the solar warmed water

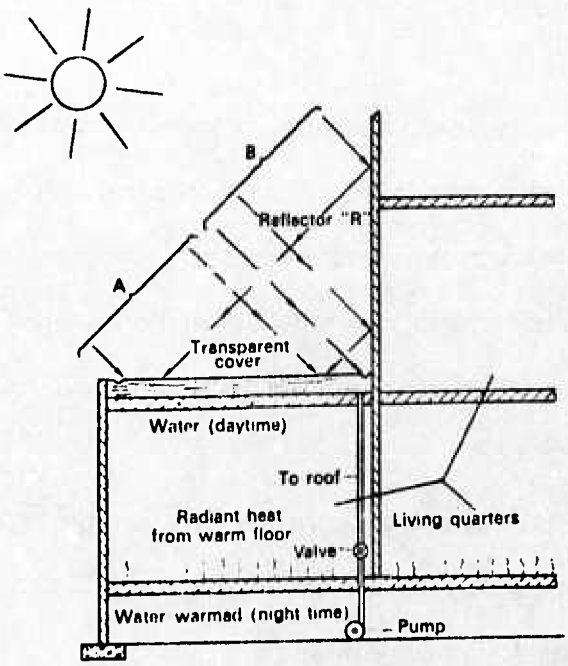


Fig. 123. Basic system for proposed "Sunny South Model" solar heating house, Thomason Solar Homes, Inc., Washington, D.C. [120].

will flow by gravity to the "pancake" heat storage under the floor. The floor is thus warmed and the rising heat warms the living quarters above. The water will be pumped to the pond (only 8-9 ft above the heat storage tank) within 30-60 minutes at a 4 lb/in$^2$ pressure.

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* Trade name - Patent pending.

The solar rays (A in Fig. 123) come in at a low angle, $30^{o}$ - $45^{o}$, and are spread out over the entire large horizontal pond area. The solar flux is only about 50-70 percent as intense as it would be if the sunlight were shining directly on a surface normal to the sunrays. This means that the rays are deconcentrated and the pond must therefore be 50-100 percent larger to intercept a given amount of solar heat. Such a large pond loses substantial heat upwards during the day through evaporation and wind convection; the pond also loses some heat at night through the large insulated area, which cannot be completely effective.

To minimize the drawback, the designers reduced the size of the rooftop pond by introducing a reflector "R" adjacent to the north edge of pond. Thus, the solar rays (B in Fig. 123) that would normally bypass the pond, are reflected onto the pond. The added reflector, with a height approximately 60 percent of the pond's width, will intercept as much solar energy as the pond itself. If a reflectance value of 70 percent from the reflector is assumed, then the increase of solar energy input to the pond would be approximately 170 percent of that which would strike a level pond directly. However, some of the morning and afternoon rays are not reflected directly into the pond, so that the overall energy input between 9:00 a.m. and 3:00 p.m. would be less than 170 percent.

From late February through March the sun is about $40^{o}$ above the horizon in Washington, D.C. (about $45^{o}$ in Phoenix). If we are designing

for a maximum reflector-to-pond ratio for that period the reflector needs to be approximately as high as the pond is wide, as illustrated in Fig. 123. (for example, pond 10 ft, reflector 10 ft). However, the ratio and angle are not deemed to be critical, and some deviation may be desirable for architectural purposes or other considerations.

Fig. 124 shows a design for a large flat roof structure which requires considerable architectural deviations. Pond no. 1, 2, 3, etc., are fairly narrow in the north-south direction. Relatively short reflectors $R^1$, $R^2$, etc., are adjacent to their respective ponds. The ponds may extend the full length of the building in the east-west direction (for example 30 to 70 ft for a home or perhaps several hundreds of feet long for a commercial building). Longer ponds and longer reflectors will have a greater percentage of the reflected light striking the pond during morning and afternoon periods.

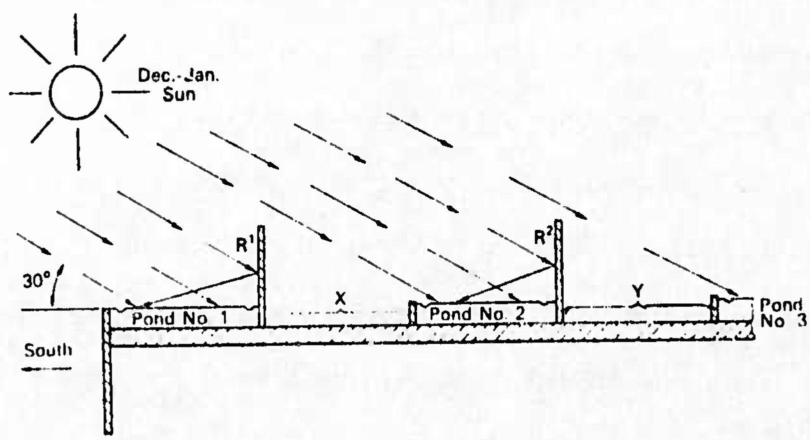


Fig. 124. A series of rooftop ponds and reflectors usable in a system as in Fig. 123 [120].

As designers have shown, much heat can be liberated from a rooftop at night. This is especially true if the relative humidity is low, good breeze, and the nighttime temperature drops to about 60° F or below, or if there is no cloud cover to block radiation to the night sky.

Employing that principle in the new system for Solar House No. 7, the water will be pumped to the roof at night. It may flood the transparent cover, or the transparent cover may be removed for the summer therby permitting ready evaporation, radiation and conduction to the cool night air. Experiments will be run to determine whether it is best to allow all of the water to flow back to storage each morning to cool the home, or to leave a portion of the water in the rooftop pond to absorb incoming solar energy and reduce ceiling heating. The answer to this question may be different under differing conditions. For example, during mild weather in autumn and spring the water likely can be left in the pond day and night. During the hot summer, in some parts of the world, it is likely that some of the cooled water should be returned to storage to help keep the house cool. To assist in keeping the house cool, a blower may be used to circulate the air, or a simple fan may be used to blow the air against the cooled floor and circulate it through the home.

Due to its simplicity and obviously low initial cost, the system is currently being considered for experimental testing in Mexico and India, for Oklahoma Indians, and in other places. Whether it will gain widespread acceptance is yet to be determined [120].

A heating system employing solar-heated air, glauber-salt thermal storage, and a vertical collector has been built and tested at Princeton, N.J. Typical January heat loads of about 12,000 Btu/hr were experienced in this 1200-$ft^2$ laboratory styled as a modern house. Air was heated in 600-$ft^2$ vertical collector in the south wall of the building by forced circulation across a black metal sheet overlaid with two glass covers. Approximately 275 $ft^3$ of glauber salt were used as storage. Collection efficiency of 46 percent was estimated for December and January, and the building was reported to have been solar heated through two winters without auxiliary energy supply [17].

A solar-heated house which has been publicized to only a limited extent was built in 1953 at State College, New Mexico. The house has approximately 1100 $ft^2$ of heated living space in one-story and two-story portions. A 457-$ft^2$ solar air heater mounted at a 45$^o$ tilt is subdivided into three sections facing in a southerly and southwesterly direction. A blackened steel sheet covered with one layer of glass is used as the primary collector element. Air is circulated from a storage unit through the collectors and back to the storage room, where 2 tons of glauber salt in 5-gal cans store the heat. Heat is transferred to the rooms by means of air circulated through the storage chamber and the necessary air ducts. Auxiliary heat is supplied by a gas furnace whenever the temperature of the storage room drops below 80$^o$ F.

Solar heating experiments were conducted for a few seasons after the completion of a solar-heated residence at Dover, Massachusetts, in 1949. An air-heating collector in a vertical position on the south wall of the building supplied heat to storage bins containing cans of glauber salt, and no auxiliary heat source was provided in the design. The house has one floor of living space with an area of 1456 $ft^2$. An attic is used for general storage and some of the experimental equipment (Fig. 125).

Fig. 125. General view of solar heated house at Dover, Mass [1].

The 740-$ft^2$ solar collector occupied the entire south wall of the house above the ceiling level of the first story. Double glazing covered blackened metal sheets 4 by 10 ft in size, figured glass being used on the exterior surface. Air was circulated in a space between the metal sheets and an insulating back panel. Heated air was conducted by ducts to one of three storage closets located between various rooms of the house on the first-floor level. The heated air passed between stacks of 5-gal salt cans and, after its heat had been transferred to the salt containers, returned to the collector panels for reheating. The solar collector was divided into three sections, each connected directly to one of the storage closets (Fig. 126).

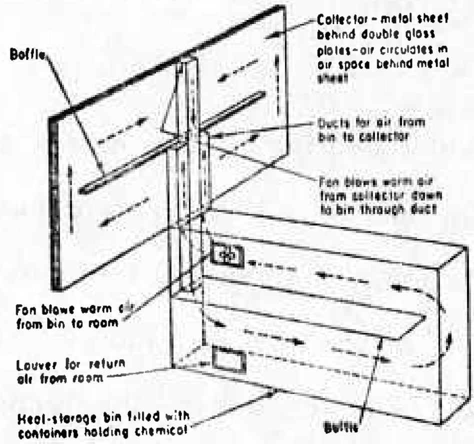


Fig. 126. Schematic of heating system for solar-heated house at Dover, Mass. [17].

Another interesting solar experiment was a solar-heated house at Amado, Arizona, about 30 miles south of Tucson. This system was completed in January, 1955, and proved equal to the design requirement that no auxiliary heat be used. It was possible to provide sufficient solar collector surface and heat-storage capacity to supply all the heat demanded by this small 672-$ft^2$ house in the comparatively mild climate of southern Arizona. The solar collector was built on the ground immediately south of the house and tilted at an angle of $53^{\circ}$ with the horizontal. It is 34 ft long, 10 ft high, and has an exposed net area of 315 $ft^2$. It was of the screen type, several layers of loosely woven black cloth being stretched across the panels beneath one cover glass. Solar energy is absorbed by these black screens, and air circulated through the screens is heated by contact with them. The

heat-storage unit comprised an underground concrete bin containing 65 tons of 4-in. field rocks [17].

A solar heating system was adapted to an existing bungalow in Boulder, Colorado, in 1947. This system was substantially of the type of the Denver installation. The general features were a 463-$ft^2$ solar air heater sloped at $27^o$ on the roof of a 1000 $ft^2$ bungalow. Solar heat was stored in 8 tons of 3/4 in. gravel in a horizontal bin. Auxiliary heat was provided by a gas furnace. Results of operation during one winter season indicated an approximate fuel saving of 20 to 25 percent [17].

A group from Southern Methodist University, Dallas, headed by Dr. Harold A. Blum, professor of mechanical engineering, described a computer assisted study that indicates that a flat plate solar collector with an area of 11,049 sq. ft and operating at temperatures from $100^o$ to $150^o$ C could supply the heating and air conditioning needs of a 100-unit apartment complex in the Dallas area.

The SMU solar collector consists of an aluminum absorber (0.064 inch thick) painted on the sunny side with a flat black paint. The absorber is separated from an acrylic cover by an evacuated space held under a vacuum of 1 torr to reduce heat losses.

The most sophisticated version of solar utilization is an experimental house, the "Solar One", designed by the Institute of Energy Conversion at the University of Delaware, Newark, which was dedicated in early July of 1973 (Fig. 127).

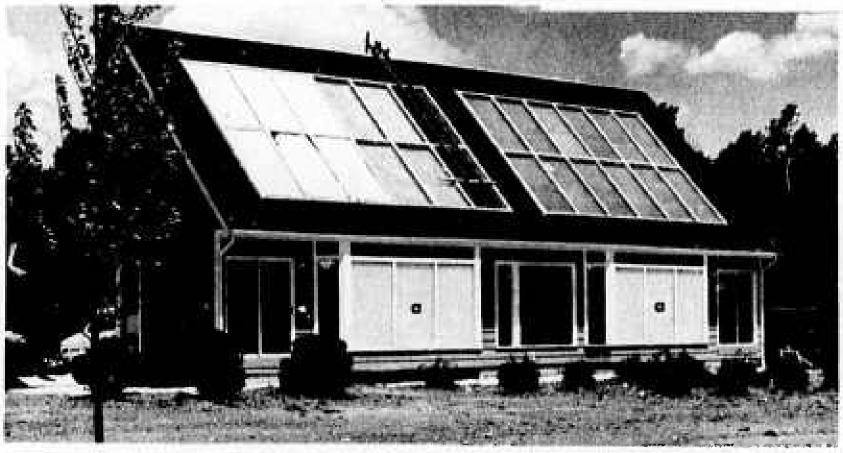

Fig. 127. Delaware house [128].

In the 1350 sq ft, two-bedroom dwelling, as described by institute director Dr. Karl W. Boër, flat-plate solar collectors containing thin-layer cadmium sulfide-copper sulfide solar cells will convert 50% of the incoming solar energy into heat and 6% into electrical energy.

Plastic-covered skylights on the $45^{o}$-angled roof contain panels of cadmium sulfide-copper sulfide photovoltaic cells, which will eventually produce 20 kwh a day of electricity, and solar heat collectors. Six additional solar heat collectors (a) on the house's south side supplement the roof collectors.

In the Delaware house, solar radiation heats the solar cells at the same time that it produces electrical power. In the winter, air from the basement is pumped into the roof area containing the hot solar panels, then recirculated into the basement where the heat melts a salt or a eutectic salt mixture encased in a 6 x 6 x 6 foot plastic container. During the evening hours when the house begins to cool down, the cooler air is circulated through the salt, extracting its heat of fusion and heating the air. During the summer, the heat pump is used as an air conditioner, operating during the evening hours to freeze another eutectic salt mixture. Then, during the day, warm air is circulated through the cold mixture, cooling the rooms.

Currently, the Delaware house uses sodium thiosulfate during the winter cycle and a mixture of sodium chloride, sodium sulfate, ammonium chloride, and borax during the summer cooling cycle. Dr. Boër admits to some difficulties in getting the salts to melt congruently and in some cases the molten salts must be nucleated before they will recrystallize. However, he believes that neither problem is insurmountable.

As for the production of electrical power for the house, Dr. Boër is at present relying on thin-film cadmium sulfide-copper sulfide solar cells, which he has been developing over the past 25 years. Currently, he is producing them with a small scale "mass production system," in which cadmium sulfide is first vacuum-evaporated onto a metal foil substrate. A

thin layer of copper sulfide is then electroplated onto the cadmium sulfide and both are covered with a metal grid electrode and a protective Mylar coating. The d.c. electrical energy harvested from the solar cells is either fed directly to household appliances and lighting systems or collected in lead-acid batteries for future use or to supplement peak power demands, which usually occur in the afternoon [128].

Of the three solar houses constructed in Japan in 1960, one, the solar space heating project at the Solar Research Laboratory of Nagoya, has been abandoned because of the lack of research staff. Two other solar houses, constructed in Tokyo and Funabashi, have operated successfully. All of these solar houses were heated by absorbed solar energy, but were cooled through a heat pump in such a way that the thermal energy was dissipated from the surface of a tubing sheet absorber during the night [101].

The collectors are of the water-heating type, with water conduits formed directly in thin sheet metal. There is no transparent covering over the collector, and the modest temperatures at which water is delivered from these units (12.8 to 26.7° C in winter) can be used only when augmented by a 3 hp heat pump.

In one application described, a 2460 ft$^2$ two-story dwelling is provided with a 1410 ft$^2$ collector on a south roof tilted 15° from horizontal. Cold-side storage is in 9600 gal of water in a basement concrete tank, and

warmed water is stored in a 2700 gal.tank. Heat is transferred to the house rooms by circulating warm water through radiant ceiling panels. The efficiency of the solar collector on the house has been estimated to be about 22 percent, based on total incident radiation. About 70 percent of the heating demand was supplied by solar energy during three winters, or based on fuel equivalent of the electric energy used, about 42 percent of the load was carried by solar energy.

A combination laboratory and residence in Capri, Italy, is heated by water circulated through 320 $ft^2$ of vertical, glass-covered metal radiator plates in the wall of a two story, 1940 $ft^2$ building. Hot water is stored in an insulated tank of 800 gal capacity and circulated by another pump to radiators in the rooms. Auxiliary heat can be supplied from a stove or electrical resistors [17].

The Mechanical Engineering Department of Pahlavi University, Shiraz, Iran has designed, built and tested a solar heated building as part of the Mental Hospital, 10 miles east of Shiraz (Fig. 128). It is a one-story building with 5,000 $ft^2$ floor area, accommodating 20-30 patients. A warm air system is presently employed for heating in winter, with no summer cooling provided. For this experiment, a flat-plate solar heat exchanger for collection of solar energy using air as the transport medium and rocks for solar energy storage, was selected. Air heated in the collector to the desired temperature is either sent directly to the rooms or to the rock bed, depending on the building heat demand. The returned air from the building is circulated back to the collector. During nights and cloudy days the air is

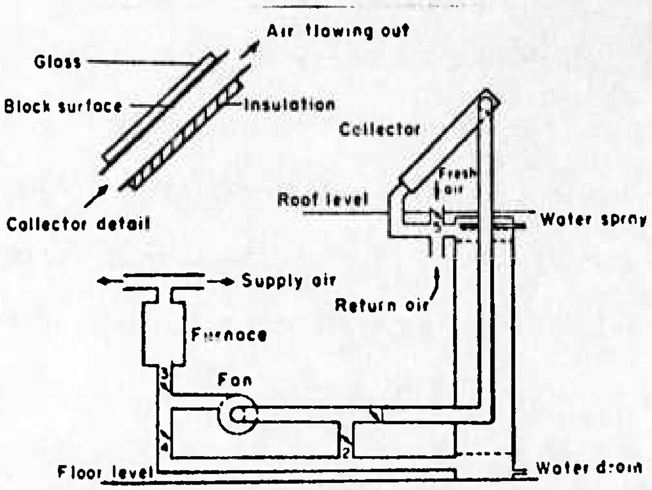


Fig. 128. Schematic of solar heated building near Shiraz, Iran [121].

circulated through the storage in the opposite direction. No attempt is made to utilize warm air for water heating. A separate solar water heater may be employed for this purpose. The single-glass, flat plate solar collector has an area of 10 $ft^2$ and an 8 $ft^2$ rock storage and is designed for solar heating and economic evaluation.

Based on this experiment, it has been found profitable to use solar heating in Iran, which features low annual precipitation and relatively cold winters. The study has been extended to eleven major cities utilizing the same principles [121].

In the USSR the Physicotechnical Institute of the Uzbek Academy of Sciences jointly with the Tashkent Regional Scientific Research

Institute for Experimental and Standardized Planning, conducted experimental research during 1968-1970 on a combined operation of heat pump and solar installations for space heating and air conditioning. The experimental chamber has an area of 6.5 x 4.5 $m^2$ and a height of 2.7 meters. During tests, adjacent rooms were heated by a conventional boiler room radiator system (Fig. 129).

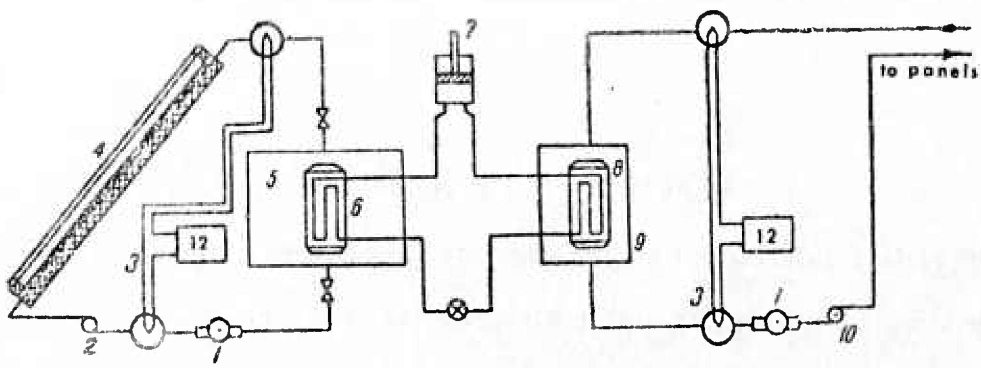


Fig. 129. Principal scheme of heat pump and solar heating arrangement, USSR [125].

During clear or partly cloudy days in winter, a 3 $m^3$ capacity heat reservoir (1) containing condenser (2) and heat pump (3) was activated. The solar collector (4) is made of stamped steel plate and placed in an insulated wooden box covered by double glass plates. Two such wooden boxes, each 6 x 1.25 $m^2$, are placed at $50^o$ elevation angle. The energy output was measured by a water pump (5) and differential thermocouple (6) equipped with a potentiometer (12).

The heat pump installation was served by a small FAK-0.7 E cooler unit having a pressurized type 2VF 4/45 compressor and an 0.6 kw motor; freon-12 was used as the working medium. The thermal capacity of this heating system for economical consideration must be calculated at 65-70% of maximum demand. Based on several years' actinometric data, heat storage capacity should be designed to allow for 3-4 consecutive cloudy days; the occurrence probability of longer overcast intervals is less than 20%.

The heat pump condenser (8) was installed in a small reservoir (7). Input of heat and cold consumed by the test chamber is measured by a water meter (5) and a differential thermocouple (6). To avoid clogging of heating and cooling coil pipes, the reservoir (7) is fed with chemically treated water. The closed cycle flow of cold-hot media inside the reservoir (7) is done by a pump (9), while water circulation through the solar heating unit is achieved by another pump (10).

Experimental tests have shown that the combined operation of solar heating and standard heat pump and radiator system makes it possible to use comparatively low temperatures of the heating-cooling agent, which increases the conversion coefficient of the heat pump and efficiency of the solar heating unit [125].

Soviet scientists conducted several tests during 1970 on tube-in-strip, flat plate, floating, and chute type solar absorbers having the same technical characteristics as those described in Chapter IV-B. These absorbers were tested under extreme summer condition at Ashkhabad, where they are to be used for solar heating and cooling of various structures.

## 2. Air Conditioning and Refrigeration

Another concern of solar engineering is the use of solar energy for air conditioning and refrigeration. The most immediate opportunity and need for the use of solar energy in cooling lies not in industrialized countries, but in hot and nonindustrialized areas.

Progress is being made in utilizing solar energy for air conditioning which will contribute to work efficiency and comfort; it may well by justified on economic grounds in many cases as more than a luxury. But it is also now clear that very efficient cooling, such as provided by the standard electrically operated vapor compression unit, is not cheap. Therefore, air conditioning by the standards demanded in rich countries is out of the question as a widespread application for dwellings in less developed areas.

A significant factor here is the strong direct relationship between the cooling requirement (need not be continuous) and the availability of solar energy, i.e., the problem of storage can thus be eliminated. Considerable efforts have gone into space cooling with or related to solar energy in several countries, such as Australia, Brazil, France, India, Israel, Pakistan, the United States, the USSR, and others. This work, which is still experimental and does not yet permit clear-cut technical and economic conclusions, ranges over a wide field, from energy utilization for cooling machines to architectural design modifications for improved ventilation and air flows.

In general, space cooling may be accomplished with systems based on the same principles as those used in refrigerating machines, except that the temperature change is less and the total quantity of heat removal is much greater. These systems include those based on power-driven vapor compression and the related jet pump cooling (both requiring high temperature), as well as dehumidification and absorption-desorption systems; the latter two may be of particular interest for solar energy application, especially when adapted to use low-temperature heat from flat plate collectors [3].

A true solar cooling system comprises a solar heating system, such as previously described, and some type of cooling unit which is operated

by solar heat. Most commonly considered are combinations of solar heat collector and heat storage unit, with some type of absorption refrigeration equipment to which solar heat is supplied. Another usable combination is a dehumidification system regenerated by solar-heated air. For completeness, several other cooling arrangements should be mentioned. These include solar air conditioners which could use solar energy but at the present time appear entirely impractical, and other cooling systems which, although closely associated with solar collectors, are not actually operated by means of solar energy. In the first category are compression-refrigeration systems of conventional type, operated by means of electricity produced from solar energy. Other than these, a solar energy system may also be adapted to cooling by use of a heat-storage unit in the summer. In a desert type climate where there are usually marked differences in diurnal temperatures, a hot storage system can be cooled at night by atmospheric air, and the thermal capacity of the storage unit utilized during the day for absorption of heat from the living quarters. The stored heat is again dissipated the following night. Day-night heat exchange can be augmented in dry climates by further heat removed by means of night-sky radiation. Because of low sky temperatures and clear atmospheres, it is possible to radiate 25 to 50 Btu per hour per square foot into a clear night sky from a surface at atmospheric temperature. Air or water can be circulated from the storage unit through a large radiating surface of metal, glass, or some other material, dissipating heat to the sky in this manner. If the storage unit is above atmospheric temperature, it can be cooled initially by atmospheric exchange in the aforementioned radiator or in a separate heat exchanger.

There are some commercial types of heat-operated absorption cooling units which could be adapted to a solar heat source, and there are several other experimental systems which might be used in this manner. The ammonia-water system is commonly used in large industrial refrigeration systems, with low-pressure steam usually being the heat supply for the cycle. For domestic use, the lithium bromide water vapor system has been employed [17].

One of the systems in commercial use employs triethylene glycol as the dehumidifying agent. This is a very hygroscopic liquid which can remove practically all of the moisture from air with which it is intimately contacted at room temperature. This moisture can then be removed from the glycol solution by heating to about 200° F and vaporizing the water into another air stream. After cooling, the solution is then ready for reuse. A glycol dehumidification system can be operated with solar energy by using solar-heated air as the stripping medium in the second spray chamber.

Other dehumidifying agents could be used including hygroscopic salt solutions such as lithium bromide, calcium chloride, and others. However, if glycol loss is maintained at a low level by effective mist separation above absorber and stripper, the cost of the absorbent is a minor item in total operating expense. The lower cost of these other solutions may therefore not be of enough value to offset the disadvantage of corrosiveness.

Another dehumidifier employs silica gel as a moisture absorbent. In an intermittent operation, air to be dehumidified is brought in contact with silica gel in a chamber. After moisture has accumulated in the silica gel for a sufficient time, the unit is regenerated while a second unit is employed for dehumidification. Regeneration of the silica gel involves heating it several hundred degrees Fahrenheit, driving out the adsorbed moisture. After the bed has cooled to room temperature, it is ready to be used again when the second unit requires regeneration. This system does not appear as well suited to solar operation as the glycol type because of the considerably higher regeneration temperatures required.

In contrast with an appreciable number of solar heated structures, no buildings have yet been cooled with solar energy. Certain components of solar cooling systems have been given full scale tests, and solar energy has been used to supply heat to equipment which might ultimately be used in a complete cooling system. Other efforts have been directed toward the design of a small, complete solar cooling system, perhaps adequate for cooling a single room, but full operation has not commenced.

As indicated in the foregoing descriptions of solar heated houses, cooling systems in some of them involve the use of certain components of the solar heating system. However, the energy for operation of such cooling units does not come from the sun, and as such are excluded from this study.

Thus, the developments described here are limited to those involving use of the sun as the principal energy source in transferring heat from the inside of buildings to the outside atmosphere [17].

Refrigeration, ice making, and other methods of food preservation by solar energy is considered as perhaps the most important possible new application in less developed areas. The use of solar energy for refrigeration has the apparent advantage that the energy supply is generally at its maximum when it is most needed. Food spoilage is highest in hot countries where simple refrigeration could save a good deal of food, make possible more even distribution of the food supply, and a more stable level of prices. One of the most promising solutions would be the introduction of ice making with solar energy through small plants now available in prototype, and shown to be capable of producing ice comparable in cost with that delivered from other sources [3].

The following is a brief review on more of the above activities in various countries.

## Australia

In Australia much effort has been expended to produce cooling by other natural processes without resorting to expensive refrigeration. Natural air conditioning is particularly pertinent here because the continent lies mainly between 10 and 35$^{o}$ south latitude, and is characterized by vast desert areas where extremely high temperatures and low humidities prevail.

Experiments with rock piles and plastic rotary generators have been conducted, and a new development of a unit air cooler using a plastic heat exchanger with evaporation-cooled plates, presently is in testing stage. The operating principle of this cooler is simple. Hot outdoor air is blown through passages formed by dimpled heat exchanger plates with every alternate passage traversed by room air into which water is sprayed. The room air is cooled by the evaporative process, but its humidity is increased at the same time and so this air is exhausted to the atmosphere after it has completed its cooling function of the heat exchanger plates. The basic unit which has been tested is a cooler suitable for a single room, but the originators of this system feel that it can be extended to meet the needs of a typical dwelling. Since the cooling process is one of essentially constant moisture content, the process is not suitable for regions with high humidities, but it does hold promise for large areas in Australia where extremely high temperatures are prevailing with moderate or even low absolute humidity [38].

Australia has vast areas which urgently need population and development, as about 40 percent of its land area, but only about 4 percent of its population is in the tropics. Hence there is a clear need for some economical means of controlling the climate in Australia's underpopulated tropics so that more people can be attracted to live there. Thus the prospects for air conditioning by solar energy can be considered quite bright [123].

## Brazil

As early as 1937 there were several attempts made in Brazil to adapt a parabolic reflector to an absorption refrigerator; however, the work never passed beyond the experimental stage.

Since 1960, the Center for Studies in Applied Mechanics (CEMA)* has conducted a more detailed study of problems on the internal arrangements of this type of refrigerating unit and harnessing of solar energy by means of a fixed conical reflector specially designed for applications of this type.

Fig. 130 gives a diagram of the refrigerator, based on a

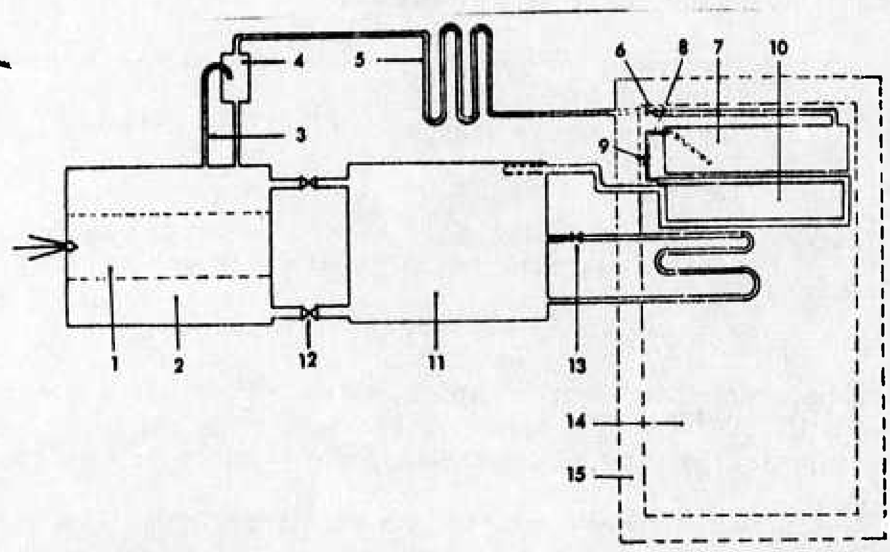


Fig. 130. Schematic diagram of solar refrigerator unit, Brazil [127].

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* CEMA was organized in 1952 as an affiliate of the National Institute of Technology, Rio de Janeiro.

generator consisting of the heating chamber (1), generator casing (2), vapor outlet duct (3), and separator(4). A two-stage condenser is used, the first stage (5) being outside the cold chamber (14) and the second stage (7) inside it; the two stages are separated by check valve (6). The evaporator (10) is preceded by the liquid outlet capillary duct (8) and the expander (9). The absorber (11) is connected to the generator by constant-pressure valves (12), with an auxiliary coil equipped with control valve (13). The cold chamber (14) forms the interior of the refrigerator (15).

The generator (2) which contains a rich 40 percent solution of ammonia in water, receives the solar heat concentrated either inside it (when a solar cell or a parabolic concentrator is used), or outside the cylindrical receiver (when a conical reflector is used). The $NH_3$ vapor liberated from the ammonia solution by heating it to $70^{\circ}$ C under 8 atm pressure passes through duct (3) into the separator (4), which frees the ammonia vapor from the entrained water vapor. The water vapor content is relatively low, 1-5 percent (according to the temperature), but it is important that it be removed to prevent icing of the ducts.

From the separator, the vapor passes into the coil (5), where its temperature falls to about $50^{\circ}$ C with a corresponding pressure drop to 5.2 atm. The second stage of the condenser is inside the cold chamber, so that part of the excess cold is utilized for condensation, thus eliminating moving parts, such as circulating pump or fan. From the liquid ammonia

tank (7) the capillary duct (8) feeds the expander (9), which discharges into the evaporator (10) where the pressure is held at about 3.6 atm. In the absorber (11), where the pressure is only 3.0 atm the vapor is continuously absorbed, progressively enriching the solution. The auxiliary coil (13) holds the pressure constant until the pressure in the generator falls below 3 atm. As soon as this level is reached in the generator, $NH_3$ will be exchanged through the constant-pressure valves (12), regenerating the rich solution, so that the cycle can repeated.

The required heat will be supplied during four hours of exposure to sunshine, and the capacity of the condenser (7) is sufficient to ensure uninterrupted operation for 24 hours. The refrigerator box has a useful capacity of 9 cubic feet (about 255 liters) or about 12 cubic feet of gross internal volume. The prototype unit was designed for 32 kg of $NH_3$ (16 kg of which were effectively circulated) at 48 kg of water, or a total of 80 kg rich solution in the generator and 64 kg of diluted solution in the absorber at the beginning of the cycle. The condenser charge is sufficient to maintain the cold for 24 hours [127].

France

The Mont Louis Solar Energy Laboratory, referred to earlier, has developed a refrigerator operating on an intermittent ammonia cycle, with the ammonia solution directly heated in the zone of concentrated solar

radiation. The ammonia solution is heated during insolation, yielding ammonia gas under pressure, which is then liquified. The cold (due to the distillation and redissolving of the ammonia gas) is generated after sunset and during the night.

The apparatus, made entirely of welded steel, comprises the following parts (Fig. 131). A reservoir tank (A) is completely filled with

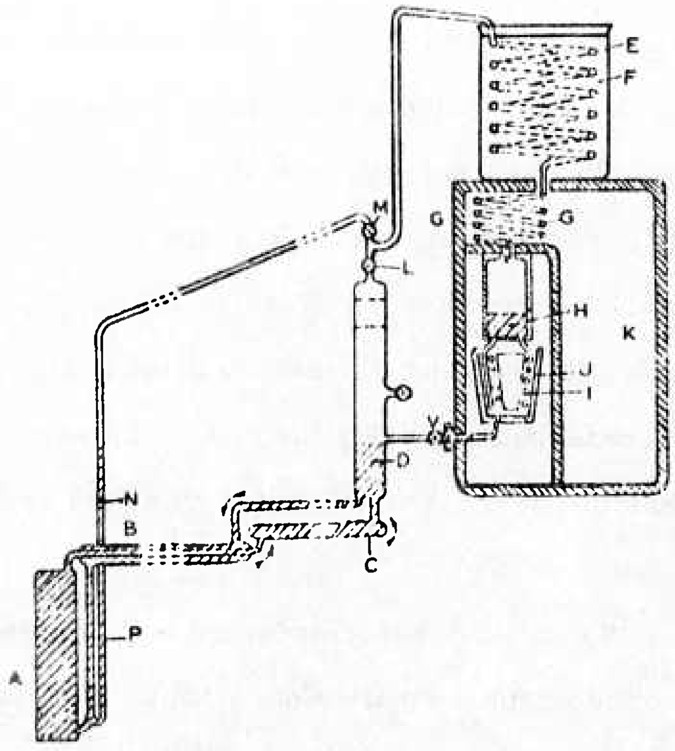


Fig. 131. Schematic of a refrigeration unit, France [130].

ammonia solution; the tank must remain cold. During the various phases of operation, its upper part contains solutions richer in ammonia than the

solution in its lower part. Heat exhanger (B) consists of concentric pipes. Solar energy is concentrated on heating tube (C), by a cylinder-parabolic mirror made of aluminum-magnesium alloy. heightened by anodizing. The focal length of the mirror is 25 cm. It rotates about its optical axis, which has an east-west orientation, by means of circular metal supports, so as to obtain the inclination giving optimum concentration of energy on tube (C). The boiler (D) contains enough liquid to permit the distillation of the quantity of ammonia gas that can be produced in a single day. Condenser (E), cooled by a non-replenishable water reserve (F), is placed in a tank protected against solar radiation by a suitable coating. A liquid ammonia reservoir (H) is surmounted by coil (G) and connects with another coil (I) surrounding the ice freezer (J); the entire assembly is contained in a cold chamber (K). Valves L and M permit distillation of the ammonia during the day and its reabsorption at night in the ammonia solution, which has become diluted during the day. The outlet (V) serves to clean the liquid residues from the evaporator (I) at the end of a refrigerating period.

Tests have been conducted on one apparatus of 1.5 $m^2$ solar collecting surface, and a smaller one with 0.18 $m^2$ area. The daily output of ice was 95 and 6 kg respectively, with the actual duration of ammonia gas distillation ranging from 4.5 to 5 hours, not counting the preheat.period of about 1.5 hours [130].

## India and Pakistan

A preliminary technical and economic feasibility study was conducted in the 1960's to establish the possibilities of using solar energy for space cooling in India and Pakistan. The system under consideration (Fig. 132) consists essentially of a flat plate solar heat collector coupled to a

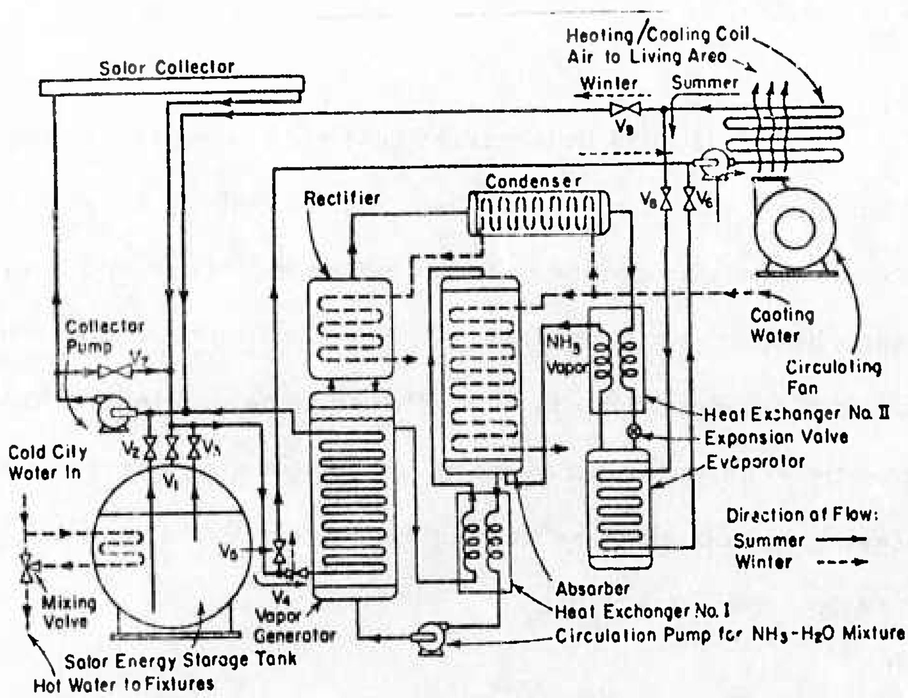


Fig. 132. Diagram of the solar heating and air conditioning system [126].

specially designed absorption refrigeration system. The absorption refrigeration unit used in this system is designed to operate at a lower generator temperature and at a relatively higher evaporator temperature (55° F) than in conventional systems, giving a very high effectiveness of heat and mass transfer throughout the installation.

Tests on this design have been conducted at MIT, using a flat plate collector similar to the one in the MIT Solar House IV. The air conditioning system essentially consists of a solar heat collector, an ammonia absorption cooling unit, an air-to-water heat exchanger, and a heat storage tank. The main components of the cooling unit are: a generator, rectifier, condenser, evaporator, water cooling coil, and an absorber.

It was determined that such a system would be technically feasible in a climate such as that of New Delhi. Most of the cooling load occurs during the periods of high solar incidence and hence very little overnight storage is necessary. For the month of May the peak value of available refrigeration is 84.5 Btu/sq ft per collector-hour. This system would become economically attractive if a solar heat collector could be built to last long enough to be depreciated over 10 years, under India's and Pakistan's climatic conditions [126].

## USA

In Phoenix, Arizona, a prototype building has been kept within the comfort zone during a period of more than 18 months by the operation of a unique solar heating and sky-cooling system. The structure uses shallow ponds of water which are in thermal contact with the metal ceiling of the room to provide both thermal storage and temperature modulation. Horizontal

plastic panels above the ponds consitute the roof of the building, and these can be pulled away from the ponds during winter days to permit the rays of the sun to warm the ponds and thus heat the house. In the summer the situation is reversed and the insulating panels are removed at night so that the ponds can be cooled by evaporation and by radiation to the sky [38].

The Solar Energy and Energy Conversion Laboratory of the University of Florida recently conducted tests on a jet refrigeration system using flat-plate or non-concentrating collectors which functioned even on cloudy days [47]. The laboratory has been experimenting both with small and large (5 ton) units. Flat plate collectors heat water which is then circulated to drive the ammonia from the water in the system's generator. The ammonia vapor is condensed and then expanded to provide evaporative cooling; the ammonia vapor is then reabsorbed into the water to repeat the cycle. The solar absorber in some systems is combined with the ammonia generator and all the equipment is installed behind or under the absorber. A small 4 x 4 ft unit can produce 80 lb of ice on a good day.

It should be emphasized again that the applications mentioned so far for this design do not require concentration of solar energy, and therefore use both the direct and the diffuse portion of solar energy [47].

Experimental programs directed toward the use of solar energy for absorption air conditioning have been carried out since 1963 by the

American-Saint Gobain Corporation and the University of Wisconsin. In the American-Saint Gobain studies, steam at atmospheric pressure was produced in a heat exchanger through which solar-heated air was circulated. In practical application, the steam would be used as the heat source in a commercial type of absorption air conditioner formerly manufactured by the Servel Corporation. The refrigerant generator in one model of the Servel air conditioner was heated by steam produced in a small gas-fired boiler, for which the solar collector and heat exchanger would be substituted. The object of this investigation was therefore the use of an existing conventional heat-operated air-conditioning system in so far as possible, with the conventional heat source being replaced or augmented by solar energy.

The Servel air conditioner, now being manufactured by the Arkansas-Louisiana Gas Company, employs an absorption-refrigeration cycle with water vapor as refrigerant and lithium bromide solution as absorbent. A schematic diagram of such a system is shown in Fig. 133. The cooling

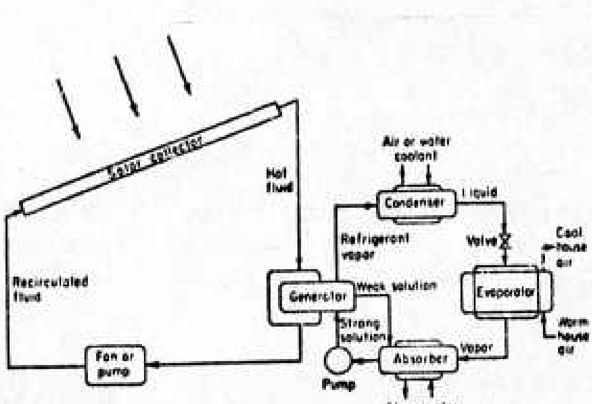


Fig. 133. Schematic diagram of an absorption-refrigeration cycle system, USA [17].

effect is produced in the evaporator, where water vaporizes at low pressure and at temperatures in the 40 to 50° F range. The vapor is then absorbed, and the resulting lithium bromide solution is pumped to the generator, where heat from burning gases produces water vapor for subsequent condensation and return to the evaporator.

In the experimental program directed toward the design of a suitable combination of this unit with a solar heat supply, a solar air heater of 128 square feet at a 27° slope with the horizontal (40° latitude) was used. Various glazing arrangements were tested, and heat-recovery efficiencies at temperatures necessary for steam generation were measured. Since the data indicate that hot air can be supplied from an overlapped-plate type of solar collector to a refrigerant generator at temperatures above 250° F at efficiencies above 25 percent, the operation of a unit of the Servel type by means of solar energy is entirely possible.

Other media can be used for supply of solar heat to a refrigerant generator. Water from a solar hot-water heater at a temperature well below the boiling point would be a satisfactory heat source for a refrigerant generator operating at 170 to 180° F. Other arrangements could involve steam supply from a collector similar to the solar water heater, and the refrigerant generator itself could be a large solar collector [17].

USSR

The Physicotechnical Institute of the Turkmen Academy of Sciences has designed and tested a solar absorption refrigerating unit with an open type regenerator. This installation will be used for space air conditioning in dry sunny southern regions of the Soviet Union. The system (Fig. 134) works in the following way: in evaporator (7), water is cooled by partial evaporation to 7-12$^{o}$ C; passing through absorber (8) the water vapor is absorbed by strong lithium bromide or lithium chloride salt solutions. The yielded absorption heat is channeled by absorber coils (9) through the cooling water. The weak solution from the absorber is conveyed by pump (11) through heat exchanger (6) into the solar collector (1) for regeneration; the lower part of the solar collector has thermal insulation (2) which serves for regeneration of the solution. Flowing in a thin layer, the solution is heated by solar radiation up to 45-60$^{o}$ C, increasing its concentration by releasing water through evaporation. From there the solution flows back through a container (3) having a float (4) and a valve (5), into the absorber (8) to repeat the cycle. Any air entering the absorber through leakage or dissolved in fluid is eliminated by vacuum pump (10). The solar collector (1) acting as regenerator can be in the form of an open basin with a heat insulated bottom.

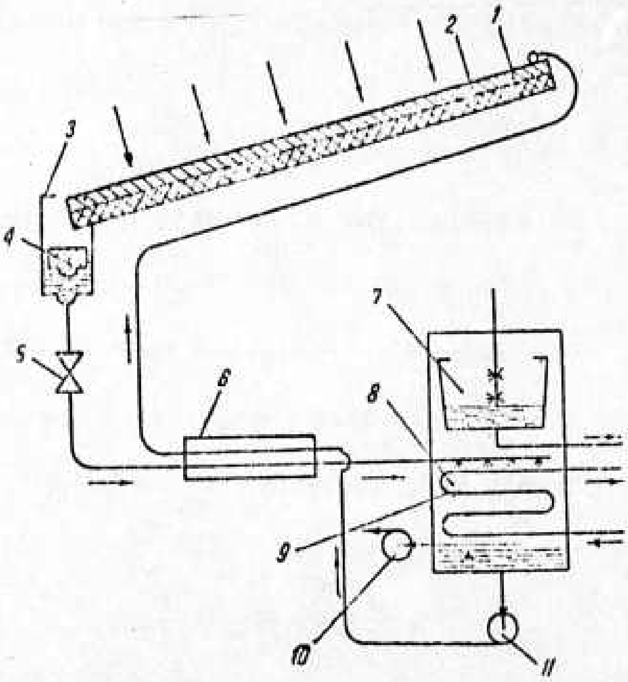


Fig. 134. Schematic of a solar absorption refrigerating unit, USSR [131].

To obtain cold water at 7-12° C temperature suitable for air conditioning the lithium chloride salts should be used, being less aggressive on metal and cheaper than lithium bromide salts [131].

The same institute in 1970 designed and tested a solar absorption refrigerating unit at Ashkhabad, Turkmen SSR (a variant of the system in Fig. 134) using an open plate generator and sprinkler chamber. In a dry and hot climate, this installation with sprinkler chamber is more advantageous than other models, as the heat losses in the cooling room are much larger then the capacity of the solar cooling installation. In addition, this system

can work day and night (at night as an evaporating conditioner) and as such is recommended in regions with dry and hot climate with moderately cool nights.

This installation (Fig. 135) is composed of solution regenerator (1), gutter (2), floating regulator (3), heat exchanger and sprinkler (4), absorber (5), evaporator (6), sprinkler chamber (7), vacuum pump (8), pumps (9, 10 & 12), check valve (11) adjusted for uniform sprinkling of nozzles (13), drip pan (14), and a fan (15).

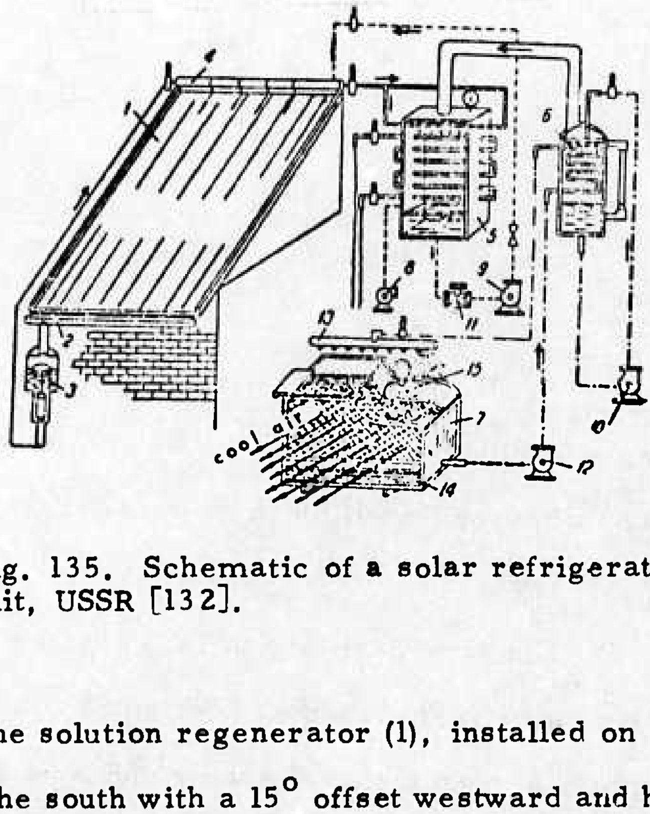


Fig. 135. Schematic of a solar refrigeration unit, USSR [132].

The solution regenerator (1), installed on roof of a building is faced toward the south with a $15^{\circ}$ offset westward and has an area of 4.8 x 4.8 meter. Heat exchanger and sprinkler (4) is made of double pipes; the heat exchanger has an area of 0.33 $m^2$, and the sprinkler (made of stainless steel) is 33 mm in diameter, with 3 mm dia. holes at 40 mm

intervals. Absorber (5) consists of 84 pipes (6 rows, 14 pipes each) with 21 x 2 mm diameter, and a total length of 760 mm.

In general, the principles, operation cycle, and type of salt solutions are the same as those for the previous installation in Fig. 134 [132].

In summary, considering space heating and cooling as the most promising practical application of solar energy in the future, the foregoing provides a look at the considerably broader scope, diverse inventions and test results achieved by various countries. The intention is primarily to introduce the technology of solar space heating and cooling to technical readers who are not specialists in any solar-utilization fields, and secondarily to the general reader interested in solar scientific and engineering developments.

D. Solar Cooking.

A solar cooker is a solar energy exchanger designed specifically to deliver heat to foods, for the purpose of raising their temperature and causing the chemical changes associated with the process of cooking. In supplying the required energy, the solar cooker supplements, and to some extent replaces conventional fuels.

A practical solar cooker must deliver an adequate quantity of heat within a reasonable time, and at temperatures ranging from near ambient to about $200^{\circ}$ C. To reach the middle and upper temperature ranges, solar concentrating devices must be used. Equipment design has evolved along two lines: the technique of concentration, and the degree to which it is used. A focusing or direct type cooker uses a reflector to concentrate beam radiation onto the food or onto a cooking vessel. Solar energy is intensified by a factor typically in the range of 20 to 100, which is effectively equivalent to an open fire as a source of energy for cooking. The open type cooker is typically an insulated box with a transparent window facing the sun. Additional radiation reflected into the window by flat reflectors arranged around it results in a solar intensification factor of 2 to 4.

The principal requirements for a solar cooker to be successful can be summarized as follows:

o Effective cooking requires that it be capable of providing a sufficient energy rate, at the needed temperature, to the desired quantity of food.

o It must be sturdy enough to withstand rough handling and use, and to resist damage by wind, for the desired lifetime.

o It must be sociologically acceptable and fit in with the cooking and eating habits of the users.

o It must be economically possible for the user to obtain a cooker at an allowable cost [133].

The solar cooker could be of enormous practical value in underdeveloped countries, whose greatest and most accessible natural resource is abundant sunshine, but which are lacking in conventional sources of power or fuel. Several types of practical solar cookers have been developed during the past ten years. Construction of most of these solar energy devices is based on the use of either concave or plane mirrors, engineered from very precise design calculations for thermal efficiencies and capacities.

Practical, simplified solar cookers have reached their most advanced stage in India (Fig. 136 & 137) where the number of sunny days far outnumber overcast days; thus the heat storage problem is not so pressing.

This fact, combined with the shortage in India of conventional fuels, makes solar cooking an attractive possibility.

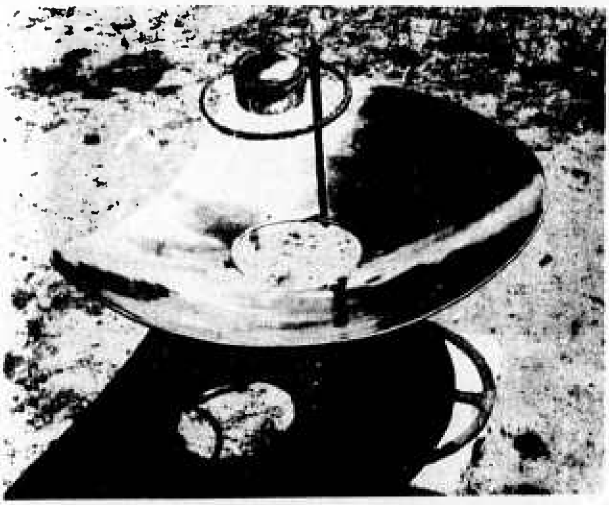

Fig. 136. Commercial model of a small solar cooker developed by the Indian National Physical Laboratory, New Delhi [20].

Fig. 137. A 44-in. square polished aluminum reflector for a solar cooker designed by the Indian National Physical Laboratory, New Delhi [20].

Besides reflector-type cookers, there are other solar applications using the heat box. In the heat box the solar rays, although not so concentrated as in the reflector type, are applied directly for cooking. A portion of the direct rays is transmitted through the glass cover of the heat box and absorbed by the black walls of the interior. Some of this absorbed heat is lost by reflection from the glass cover itself, the rest being used to raise the temperature of the box and of its contents, such as food. When the temperature of the interior increases, more heat is lost from the surface, a process that continues until equilibrium is reached between the two temperatures and the temperature of the food itself. A difficulty with all heat boxes is that they posses to a greater or less extent a thermal inertia that works to retard heat buildup so that the incident solar heat cannot act instantaneously on the material to be heated.

Heat boxes that collect the solar heat by means of horizontal covers (rather than by reflectors angled to face the sun directly) cannot be used successfully unless the sun elevation is at least 65°. Longer hours of cooking, or an increase in heat buildup through more effective insulation, might give better overall efficiency, but even with these improvements the horizontal type of heat box would still need a minimum solar elevation of 40°, which limits its use to certain bands of latitude.

The light-transmission factor for clear glass depends to a certain degree on its refractive index, its thickness, composition, and on the angle of incidence greater than $40^{o}$ or $50^{o}$ with the sun. At normal radiation incidence, the transmission capacity of glass plates 2 mm thick is assumed to be 0.86 for a single plate and 0.75 for a double plate. The transmission capacity of two glass plates at incidence angles of 45, 60 and 75 degrees is assumed to be 0.72, 0.65 and 0.35 respectively.

However, a solar cooker with a reflector has three distinct advantages over the horizontal heat box. The permissible range of the sun's elevation for efficient heating is substantially greater, i.e., it can be used longer each day and over a wider range of latitudes; thus the reflector makes it possible to use a solar cooker in the early morning or late afternoon hours, whereas the flat horizontal cook box is limited to the midday hours, when the sun is in the vicinity of zenith. Finally, the heat box has a relatively high thermal inertia, whereas the reflector-type cooker starts operating almost immediately on exposure to the sun. The reflectivity of a silver-plated reflector can be as high as 96 percent. Aluminum or anodized reflectors have a reflectivity of between 70 and 85 percent, depending on the purity of aluminum, grain composite of the aluminum film in the case of anodized sheet, surface hardness of the aluminum alloy, and other factors. A reflector with an effective surface of 10 square feet absorbs a total of 1000 watts of incident radiation.

Spherical or parabolic reflectors provide the maximum concentration of radiation in solar cookers. Spherical reflectors with a large bending radius must, when applied to solar cookers, be equipped with a device for supporting the cooking compartment at exactly the right distance from the geometric center of the reflector. A parabolic reflector does not have these disadvantages, since the image it produces is clear, small and sharp. The astigmatism of the parabolic reflector is greater than that of the spherical reflector, but because the image is so much smaller, it stays in focus much longer. For this reason, as well as being much easier to handle, the parabolic reflector must be considered the better of the two types.

The design and construction of the cooker or food compartment will depend on the effective surface and reflectivity of the reflector. If the reflector surface is too small, the amount of heat focused on the cooker will not be enough to make up for the heat losses, and the temperature will not build up sufficiently for cooking purposes. A larger reflector surface means that the capacity of the cooker can be increased, but the reflector tends to become cumbersome or expensive to construct. A surface of 6 square feet with a reflective power of 75 percent has been found to be the minimum size for cooking purposes under favorable conditions of sunshine, air temperature and wind velocity. The efficiency of a reflector surface of about 10 square feet is much higher. The optimum size of reflector surface for a solar cooker seems to be about 12 square feet, sufficient for cooking an average meal for five to six persons.

Since the cooking compartment must be designed according to the size of the reflector, the focal point or focal length of the reflector also affects the design. Focal lengths greater than 3 feet are not practical owing to random energy losses. Reflectors with focal lengths of between 10 and 30 inches have been used in various designs and testings, and it has been determined that a focal length of about 18 inches is the most appropriate for reflectors with an effective surface of 10 square feet. In considering the focal lengths, the cooking compartment has to be kept level regardless of change in reflector position. A parabolic mirror or reflector with a diameter of 3.5 feet and a focal length of 18 inches can be reoriented within an angle of 28°, which in most latitudes is sufficient to correct for the sun's elevation angle [20].

Of the two principal cooker types, solar ovens appear better adapted to the use of thermal storage materials, besides having higher intrinsic storage capacity for keeping foods warm and permitting the extension of cooking a short time after sundown and during short cloudy periods. Augmented heat storage by use of heat-of-fusion and heat-of-transition is under consideration. Researchers have compared the heat storage capacities of several materials in the 150° to 200° C range. A mixture of alkali nitrates provides heat-of-fusion storage at 150° to 160° C; and mixtures of anhydrous alkaline sulphates undergo a solid phase transition between 191° and 239° C, with a latent heat effect of about 60 calories per gram. An oven containing about 3 kg of the sulphate mixture in the form of a flat-bottom slab is in the design stage. Unless used primarily for

storage during preheating of empty ovens, however, the alkali sulphate mixtures appear to have unusably high transition temperatures, since solar ovens seldom reach these levels during cooking. Others have suggested the use of hydrated magnesium chloride (melting point 117$^{\circ}$ C) and magnesium palmitate (melting point 121$^{\circ}$ C) as heat storage materials in specially shaped vessels supported at the focus of a large spherical reflector.

However, the whole subject of thermal storage for cooking appears to need further consideration. It is possible that focusing cookers could be used with some type of storage container to store heat during most of the day, with subsequent use for evening cooking. The development of cheap, harmless and dependable materials with high thermal capacity, moderate weight, and adaptability to cooker designs might greatly extend the potential of solar cooking [133].

Laboratory and field studies of reflective-type solar cookers have been in progress for several years. The reflective-type cooker is particularly well suited for boiling, stewing, and other wet cooking. With the use of metal plates of good conductivity to distribute the energy over the cooking surface, it can also be used for frying. It can also be adapted for baking by the addition of an insulated oven over the pan support. Like any other reflective solar exhanger, proper use is mandatory if adequate energy delivery is to be achieved; with proper use these cookers can deliver a maximum of 600 watts depending on beam radiation intensity and the condition of the reflector [135].

The reflectors generally used in solar cookers are made of plastics. Recent models use a drape-formed high impact polystyrene shell with a thickness of 0.06 inches, stiffened at the rim with a ring of thin-wall aluminum tubing of about one-half inch diameter. These shells are light in weight, sufficiently stiff to retain their shape, and resistant to damage by bending or folding. They are readily shaped in the compound curvatures required by simple forming techniques.

A reflective lining of aluminized mylar polyester film is applied to the shells with an adhesive, so that the clear film forms a protective covering over the reflecting surface. The reflectivity of this material ranges between 75 and 80 percent, which decreases with age at a rate dependent on film weathering and deterioration.

In the early 1960's, the University of Wisconsin designed and tested several cookers using plastic reflectors and standard construction principles (Fig. 138 & 139).

Performance of these cookers has been measured in the laboratory, and interpreted in terms of the energy balance for the units. Power delivered to the contents of a cooker vessel was in the range of 300 to 600 watts, depending on weather, conditions of use, and the age of reflector [135].

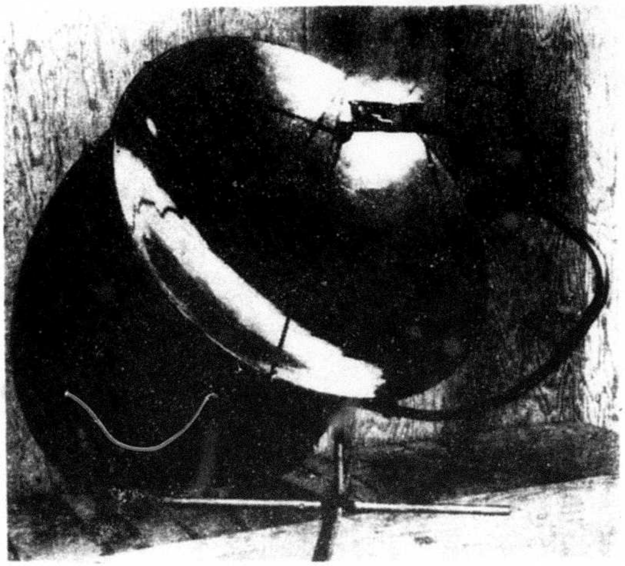

Fig. 138. The Model 2 Wisconsin Solar Cooker. Reflector aperture 48", focal length 18" [135].

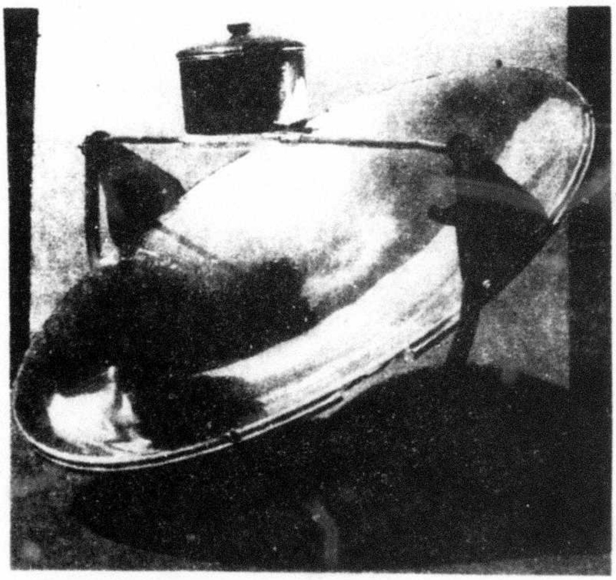

Fig. 139. The Model 3 Wisconsin Solar Cooker [135].

Cookers employing optical concentration can be further subdivided into two groups: those with rigid reflectors and those using collapsible reflectors.

Several types of the collapsible concentrating cookers have been produced and marketed. One of these employs wedge-shaped polished metal segments that fold in a manner similar to the flash bulb reflectors used in photography; when fanned out the segments form a parabolic reflector. Another cooker uses two rectangular segments of a paraboloid as the reflector. A thin coating of vapor-deposited aluminum on the plastic segments forms the reflective coating [136].

A variant of these is the Umbroiler which is the trade name for a folding, umbrella-type solar cooker. The Umbroiler combines the function of a solar reflector with a readily portable and collapsible umbrella frame and a flexible reflective fabric. With this combination, a compact, portable and efficient solar cooker is obtained. Although developed primarily for intermittent recreational use, this cocker could also be adapted for daily use in underdeveloped regions.

A schematic and the assembled solar cooker are shown in Figs. 140 and 141.

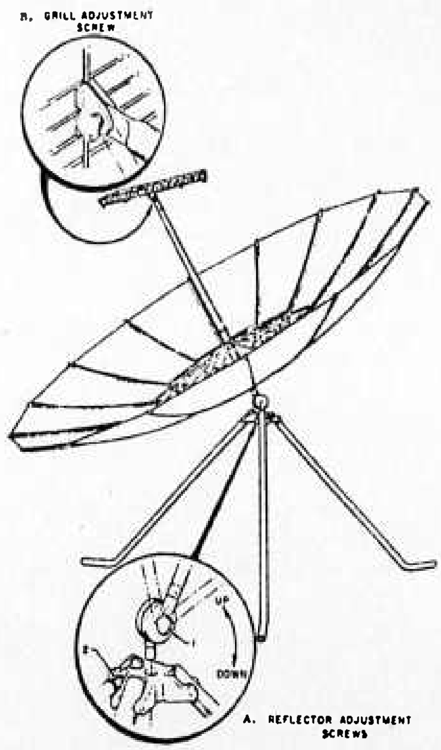


Fig. 140. Schematic of a folding umbrella-type solar cooker, USA [136].

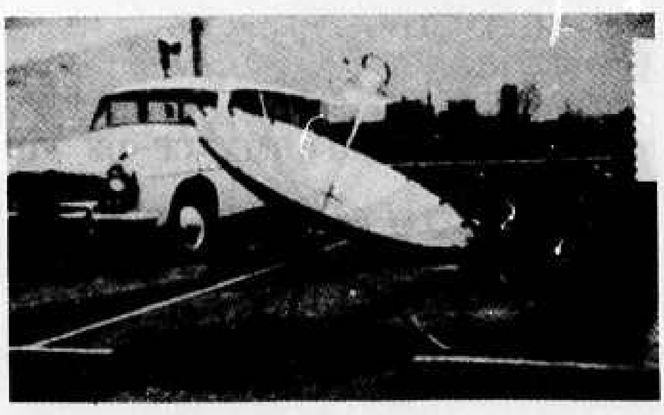

Fig. 141. Assembled umbrella-type solar cooker, USA [136].

One of the advantages of this type of cooker is its compactness and portability. The entire cooker, including reflector, support stand, and cooking surface weighs about 4 pounds and can be folded into a carrying case 4 inches deep, 10 inches wide, and 30 inches long. To assemble the unit, the folding tripod is placed on the ground, the reflector is opened like an umbrella and attached to the tripod, and the grill is connected to the main umbrella shaft.

Some changes in cooker design would make this unit more serviceable and cheaper for daily use in fuel-scarce areas where it might be the primary food cooking unit. Present cookers should probably be strengthened to meet more severe use. This could be accomplished in two ways: using stronger structural members, or by changing the design of the support. The stand could be redesigned to support the cooking surface and cooking vessel directly and at the same time also support the reflector. Heavier cooking loads could thus be accommodated. One possible modification is shown in Fig. 142.

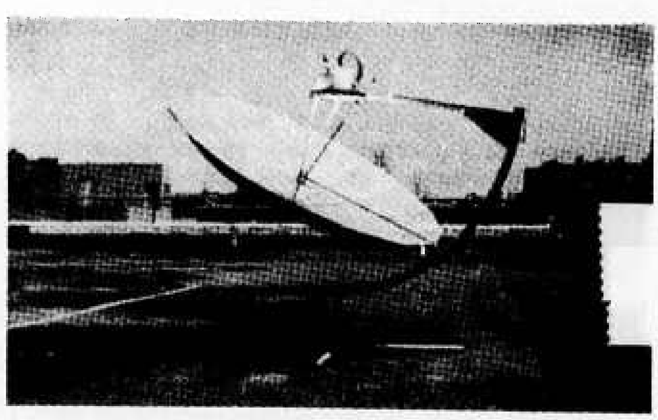

Fig. 142. Collapsible, umbrella-type solar cooker with modified support stand, USA [136].

The Physicotechnical Institute jointly with the Central Design Office, both of the Uzbek Academy of Sciences, has designed and manufactured a collapsible solar cooker. The parabolic reflector of 1.5 m in diameter and a focal distance of 0.7 m is made of 12 aluminum plated segments (Fig. 143). The cooker is carried in a casing and can be installed in 20 minutes.

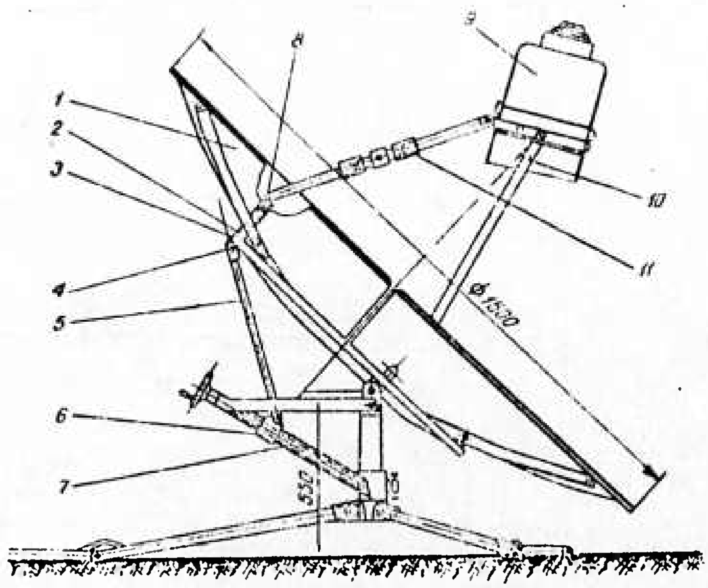


Fig. 143. Schematic of a collapsible solar cooker, USSR, (dimensions in mm) [134].

1- Reflector; 2- screw; 3- adjusting check ring; 4- lug; 5- movable rod; 6- threaded sleeve; 7- threaded drive shaft; 8- shaft; 9- cooking compartment-canister; 10- elbow pipe; 11- turnbuckle.

This portable solar cooker can also be used as a sun shade or canopy for protection against solar radiation and bad weather (Fig. 144).

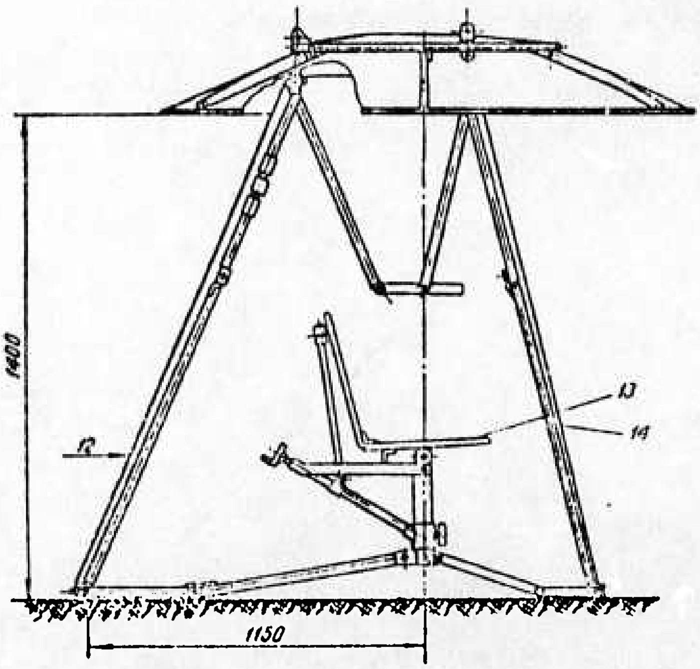


Fig. 144. Schematic of solar cooker used as canopy against sunshine or bad weather, USSR, (dimensions in mm) [134].

1-11 same as in Fig. 143; 12- canvas or tent cloth; 13 - swivel folding chair; 14- spare rod.

A large plant is under construction near the town of Bukhara, Uzbek SSR which will manufacture various solar equipment and instruments. It has been estimated that this plant will manufacture, among other products, about 25,000 solar cookers annually [137, 138]. The plant will be under the Physicotechnical Institute which will conduct various tests (see Fig. 145) pertinent to solar engineering [137].

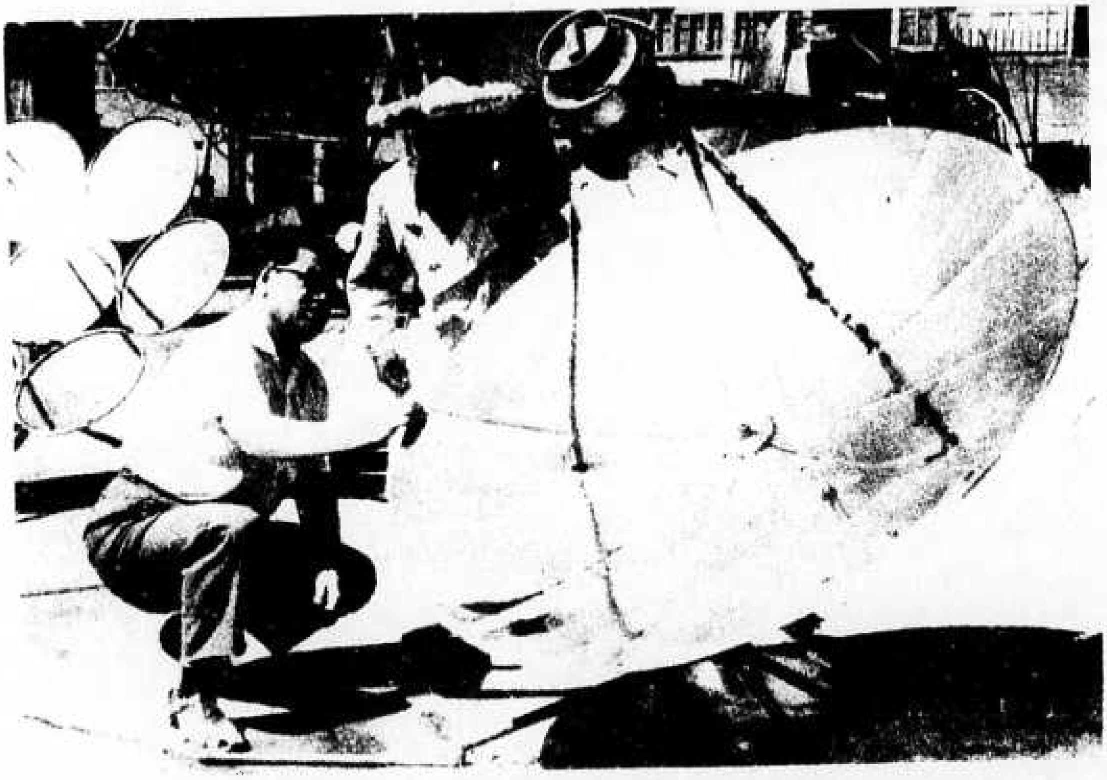

Fig. 145. View of a solar cooker in testing stage, USSR [137].

In the overall view, solar cooker development appears to have reached a point where practical application is imminent. Several cookers appear technically capable of supplementing, to a substantial extent, the cooking needs of peoples in sunny climates. However, appraisal of use prospects requires further field testing by potential users. New designs, materials, and manufacturing techniques appear desirable, both for achieving better performance and for lowering costs of manufacture [133].

## E. Water Distillation and Salt Extraction

### 1. Water Distillation

Since a few early studies which were done from intellectual curiosity rather than for any practical concern with the problem, solar distillation has passed through various stages. The first realization of a large greenhouse-type still in Chile in 1872 marked the beginning of scientific research and development in solar distillation.

In the late 1920's, a sudden revival of interest in solar distillation began, with practical development mainly in greenhouse type installations of wood and metal, and covered with window glass. At the same time, several researchers concerned themselves with systems operating at higher temperatures or in vacuum. However, intense activity in the development of solar stills in many countries came only with World War II, and in still greater measure during the immediate postwar period. Interest now has become general throughout the world, and it would be hard to name all the investigators who have contributed to this collective, sustained effort that still continues today.

In general, this new effort took the same form as in the 1920's period. A number of models were developed varying widely in shape, nature, design and material; these studies rapidly assumed a more systematic character of searching for basic data, both by experiment and from theoretical

calculation. We are thus today at a new stage in development of solar distillation, or more generally speaking, of desalting by means of solar energy [145].

Most of the known procedures for desalting may be classified broadly into three major groups according to the type of process used: physical, chemical, and electrical. Within each of these general classifications are many specific methods of water conditioning. They include vaporization, crystallization, sublimation, adsorption, ultrasonic, osmosis, ion exchange, electric-ion migration, and numerous other processes [114].

With the growing shortage and rising cost of fresh water in many areas, there is a great interest in converting sea and brackish waters into fresh water by solar distillation. Artificial solar distillation is the simplest process, in effect duplicating under more controlled conditions the evaporation and precipitation taking place on a large scale in the natural hydrologic cycle [3].

Solar distillation exhibits a considerable economic advantage over other salt-water distillation processes because of its use of free energy and its insignificant operating costs. Although these advantages are partly offset by increased amortization expenses, distillation with solar energy remains the most favorable process for small capacity water desalting in areas with considerable solar radiation. Another advantage of the process

is its simplicity. Most solar distillation plants are being or will be erected in less developed countries or in remote areas with limited sources of fresh water and maintenance facilities.

Since radiation per unit of surface is determined by natural causes, the output of a solar distillation unit can only be increased by increasing the surface or the efficiency. Capital costs and amortization rates are directly dependent on the intended output and the efficiency; they increase more or less proportionally with the increase in defined output for a given design. The overall efficiency of a solar desalting unit is determined by the ratio of product condensate to the theoretical amount of salt water vaporized, i.e., the ratio of the heat of evaporation of the condensate to the solar heat reaching the apparatus [43].

The hot-box type still is very simple (Fig. 146) and at the same time extremely rational in terms of the physical processes taking place in it. The efficiency of a still carefully and correctly built can amount to 60-70 percent. Calculations show that this figure is close to the maximum

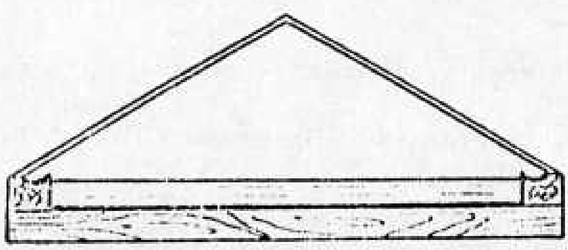

Fig. 146. Hot-box type still [142].

which can be obtained in stills made of ordinary materials: glass or plastic for the top; plastic, asbestos cement or wood for the structure; and cork or plastic for the insulation.

The capacity of such constructions varies greatly in the estimates of various researchers, which can be explained by the specific features in design of the different installations, climatic conditions and locations.

The qualitative operation of the distiller is based on the following process. Part of the radiant energy falling on the distiller is lost as a result of the reflection from the glass, the surface of the water and the bottom. However, the main part of this energy is absorbed by the bottom and the water layer and is converted into heat. Consequently, the bottom and the water in contact with it have the highest temperature in the system. The heat will, therefore, be conveyed to the ambient air in quantities corresponding to the temperature of the various parts of the installation and the thermo-physical properties of the materials of which these parts are made.

The steam-air mixture in the vicinity of the glass has a lower temperature and a greater specific gravity than near the water. Consequently the mixture goes down from the surface of the glass, and rises from the surface of the water. The angle at which the glass is set imparts a certain order to the movement, and formation of circulation flows (Fig. 147).

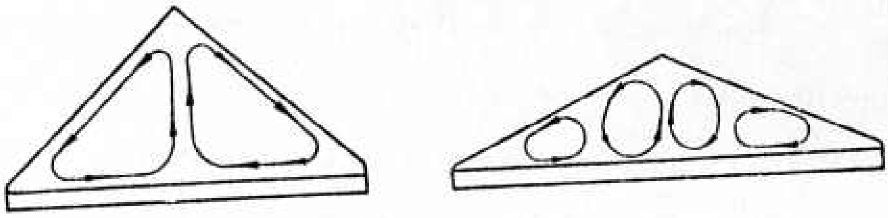

Fig. 147. Diagram of circulatory flows of vapor-air mixture in a hot-box type still [142].

In passing close to the water, the mixture is heated up and saturated with vapor which cools and condenses on the surface of the glass and runs down. This process takes place in a comparatively thin layer close to the water and glass. It practically does not penetrate into the rest of the mass, since diffusion and molecular heat conduction are low and there is no noticeable mixing of the cold and warm masses in the volume. The quantity of heat emitted by the steam-air mixture when passing in the vicinity of the glass determines the quantity of water condensed on the glass surface [142].

Heat losses occur at several places through direct and diffuse radiation partly reflected from the outside and inside surface of the cover, from the water surface, and from the bottom. Some radiation is also absorbed by the cover. The remaining radiation is absorbed mainly by the salt water and partly by the bottom. Of this latter, most is transferred to the overlying water, and only a small part is lost by conduction to the ground beneath the basin. In addition to the air-vapor convection currents, heat exchange also takes place by radiation between the warm surface of the salt

water and the condensate film on the inside surface of the cover. The corresponding heat absorbed by this film is transmitted to the cover material and lost to the outside air by convection and radiation. Most of these heat losses are unavoidable. However, the heat lost by the cover to the outside air is necessary to keep the cover cool and thus maintain operation [143].

Most experimental work has centered on the inverted-V type still shown in Fig. 146. Attempts have been made to improve its effectiveness by placing insulation under the seawater pan. Attempts to simplify and presumably cheapen the construction led Dr. Maria Telkes to design and build a wick-type still (Fig. 148).

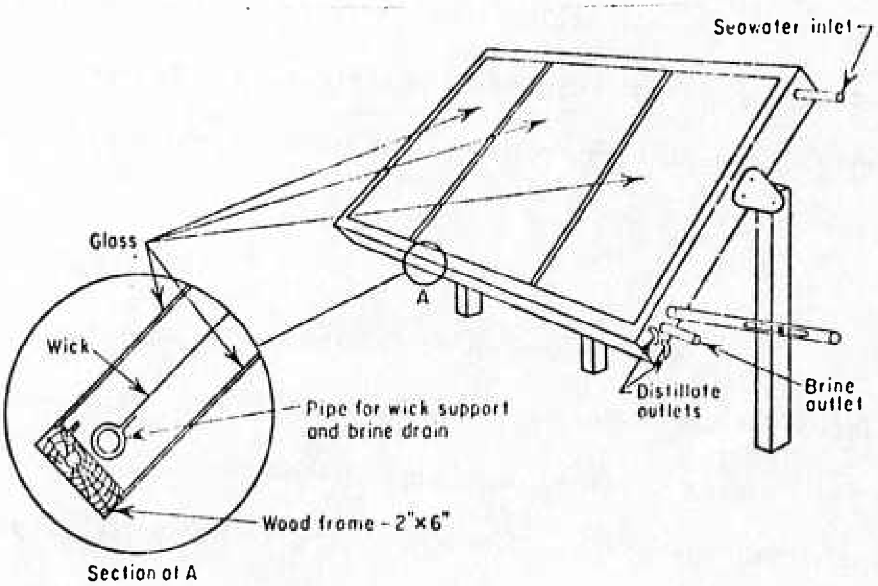


Fig. 148. Wick-type solar still [18].

This unit consists of a flat box with the two large faces of glass, and containing an absorbent cloth wick stretched in its central plane. The box has to be placed either vertical or inclined so as to be nearly perpendicular to the sun's rays at noon. Sea or brackish water supplied along the upper side of the wick saturates the cloth and thus provides a wet surface from which water can evaporate. The vapor leaving the wick enters the air stream and contacts the glass, where part of it condenses and collects in a gutter along the base of the inclined glass pane [18].

In this type of still there are no losses by heat conduction through the bottom, which saves about 10 percent of the incident energy on the distiller, but direct losses by radiation are doubled, since the heat-loss surface is twice as big as in a tray-type distiller. As a result, the heat balance will be somewhat worse. The greater specific capacity of the fabric distiller can be explained by the fact that it is inclined and in nontropical areas receives more energy per square meter than if placed horizontally.

Good technical results can be obtained from such a distiller, if it is correctly designed, carefully built, and properly operated. On the basis of experiments to date, the following recommendations are made.

In designing a distiller, it is necessary that the tray be out of the shadow of the structure. The angle at which the glass is inclined should be sufficiently large for the drops of the condensate to run down the glass and

not fall back into the tray. The glass or transparent plastic should have a surface which can be sufficiently well moistened, otherwise a mist will form on the surface and attenuate the solar rays. In addition, the installation of the bottom must have a low heat conductivity and no moisture should be allowed to fall on it as it would lessen the heat insulator properties of the material. Special attention should be paid to sealing the chamber of the distiller hermetically. Experiments conducted in such a way that a balance between the evaporated and condensed water is formed, as well as calculations, showed that even the slightest cracks in the upper part of the distiller lead to greater losses--even as a result of natural pressure--of the steam-air mixture These losses are greatly increased when the wind "blows out" the mixture, as then the distiller practically stops working. These losses can be computed. A number of authors point out the need to regularly drain the salt solution in the tray, to prevent the salt falling out on the bottom, since a salt layer would lessen the absorption of radiant energy.

Since this type of distiller has practically been brought up to a maximum efficiency, the cost of the distilled water can be reduced further only by cutting building costs. The main direction which this work should take is the use of films and plastics, and the mass production of standard boxes. Recently, a number of successful works have been carried out with the use of transparent plastic.

The idea of creating a distiller in which the water would be heated to a temperature of 50-80° C in the hot box and in which the condensation of the steam from the vapor-air mixture would take place in a separate condenser has been put forward in different forms. However, the attempts to construct such an installation ended in failure, as the specific capacity of the distiller was negligible. This is easily explained: the circulation of the vapor-air mixture in the heater-condenser is difficult, the speed of the diffusion of steam from the heater to the condenser being absolutely insufficient for the normal work of the distiller. Moreover, there exist additional heat losses which are absent in the simplest types of distillers.

It is true that in the hot box all the heat conveyed through the glass into the ambient air is lost, while in the distiller a large part of the heat passing through the glass is the heat of condensation, which has to be transferred in accordance with the working scheme of the ideal non-regenerative distiller. It is sufficient to draw attention to the fact that the efficiency of the hot box is lower than the efficiency of the simplest distillers, even though the water in them has the same temperature.

The process of desalting water can be conducted in a much more economic way from the point of view of the energy used if the principle of regeneration of heat is used in distilling. It is evident that in the distillers examined above, almost all the heat spent on the evaporation of water is then (during the condensation of the steam) let out into the ambient air and thus lost [142].

In general, many small stills of family size for providing drinking water are based on the flat-plate collector principle and are essentially simple. Provided with insulation on the bottom, they usually consist of a black heat-absorbing surface that evaporates saline water. There are many variations in arrangements and in types of material used.

These small solar distillers produce about 7-8 liters per square meter of evaporating area in summer and one liter in winter, averaging some 4-5 liters per day and 1.5-2 $m^3$ per year per square meter of evaporating area.

Large-scale solar distillers face a much more difficult situation, at least in the capacity range above 50,000 liters a day. They must usually be competitive with fresh water transported from distant sources or with other demineralization processes, or with both. The large solar distillers so far tried are mainly of the single-effect type, as in the case of those installed ranging in size up to 3000 square feet, and afford an opportunity to study different designs and materials. The large but simple distillers are basically an extension of the small ones; they obviously afford some economy of size, but unfortunately drop in efficiency. Large solar distillers may incorporate various refinements, such as forced convection and multiple-effect distillation, thereby improving efficiency but adding to investment cost if not to product cost.

Technically, it is also possible to use solar concentrators for the production of steam, to be subsequently condensed to fresh water. This steam production may be combined with production of electricity and also with demineralization by electrodialysis [3].

Whichever type of solar distiller is used, the collector is the big item requiring cost reduction. The most radical way to reduce this problem is to use a lake or the sea as the collector, as in the so-called Claude process (see Chapter II-B/2) which uses the thermal energy of the sea and a surface condenser to produce fresh water after drawing steam through a vacuum chamber (and driving a turbogenerator on the way) in a low-pressure and low-temperature differential system. A land-based pilot project, essentially using this system, has been drawn up in Chile [3].

For large-scale evaporation or distillation with solar energy, the Claude-type process may hold the most promise, particularly when combined with power production. Simple solar distillation on a large scale appears less promising at the moment and may under certain circumstances be better carried out by cascading of small individual units, which would also save the cost of distribution from a central unit [3].

If we consider the thermal energy of the sea, where power is generated by bringing cold and warm sea water together in one floating plant, it becomes logical to use these same ingredients for the production of cheap fresh water from salt water. Fresh water can be produced very simply by the process shown in Fig. 149.

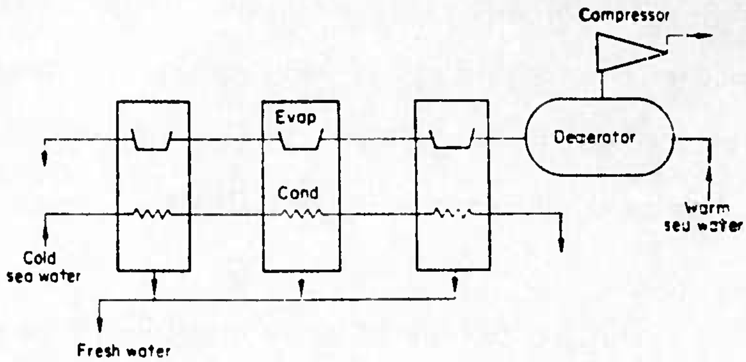


Fig. 149. Diagram of water desalting flash cycle of a sea plant [90].

Warm salt water is deaerated and enters a large vacuum chamber of low enough pressure so that it boils. The steam is conducted to a condenser and cooled by the cold water from the power plant outlet, where it condenses into fresh water. While this is basically a very simple process, there were until recently serious problems that appeared to prevent economical development of this process. First, the heat of vaporization of the vapor boiled off from the water must come from the water itself. It takes 1000 Btu of heat to evaporated one pound of water, hence this much heat requires cooling 100 pounds of water through $10^{o}$ F. Therefore, in a very rough approximation, one can get only 1 or 2 pounds of fresh water from each 100 pounds of warm water furnished to the evaporator. However, means have now been found to reduce the power required for deaeration and pumping to a very small amount. Since the power is cheaply generated in the floating sea thermal power plant, the combination of available water and power can produce

fresh water for a cost of approximately 3 to 4 cents per thousand gallons of water. This puts a whole new dimension on the possibilities of producing fresh water for industrial, agricultural, and domestic purposes.

The fresh water produced in a floating plant at sea must be transported to shore. Analysis of transport cost indicates that it would not be more than 5 cents per 1000 gallons from a typical plant location with respect to the shore. It has been estimated that more than a billion gallons of water per day can be produced by a sea power plant of 100 MW capacity. A very major advantage of the combined sea thermal power and water plant is the flexibility and economic possibility of making any quantity of water, hence the sea thermal plant is equally adaptable for large and small scale fresh water production.

Let us look briefly into the most controversial item of a solar distiller, namely, glass and/or plastic. Among researchers there are divided views on the practicability of glass versus plastic, a major component of a solar distiller. Such opinions are based, for the most part, on various tests conducted under laboratory conditions which do not provide the same results as under natural working conditions, different geographic location, and varying production requirements.

Glass transmits optical and other short wave radiation, but is opaque to the long-wave infrared. From this it follows that short wave energy, which comprises the bulk of the solar energy, can pass through the

glass cover of a solar distiller or a greenhouse and heat up whatever material on the inside is capable of absorbing the energy. The disagreement involves the explanation of the manner in which the heat absorbed is prevented from leaving the enclosure. The usual explanation is that the heated materials within the enclosure radiate long wave energy to which the glass is opaque, as noted above. The glass then reflects this energy back into the enclosure and thus acts as a trap for the energy. This greenhouse effect occurs in any enclosure having a transparent cover, and is the basis on which all low-temperature solar collectors are designed [18]. In addition, glass is much better than plastic since it produces film condensation, letting the solar energy through with minimal attenuation. Plastics typically produce dropwise condensation, each droplet forming a small crystal which reflects much of the incoming solar radiation [47]. To date, most solar still research funds have been spent on conventional glass cover design.

However, proponents of plastic have found more promising results in desalination processes based on plastics. Promoters of reverse osmosis, ultrafiltration, and electrodialysis have used research funds for improving plastics and have thereby obtained superior properties and increased efficiency; meanwhile confidence in the future of glass covers is based on their present use in large stills where more innovative plastic covers have not yet proved to be of long-term merit.

Different designs and various configurations of solar stills have been the object of intensive research and development, but practical considerations exclude all except the so-called greenhouse type. Morever, the operation of any solar still of the greenhouse type is based on the same theoretical considerations, so that the actual designs differ only in geometry, in the means of cover support, in feeding the salt water and discharging the brine, and in the construction materials, principally the cover.

Whatever the design the still must be completely water - and airtight. Distillate leakage is a net loss; brine leakage increases the thermal conductance of the soil beneath the still and thus increases heat losses; and vapor leakage, which can be increased by wind, causes loss of both heat and evaporated water. High radiation absorption is aimed for by all designers, so as to reach high water temperatures and consequently high rates of distillate output.

Loss of condensate by dripping from the cover back into the basin is equivalent to distillate loss. The condensate will flow smoothly along the under surface of a glass cover, as long as a slope of $10^{o}$ is provided.

Schematics of some stills with glass or plastic roofs are shown in Fig. 150.

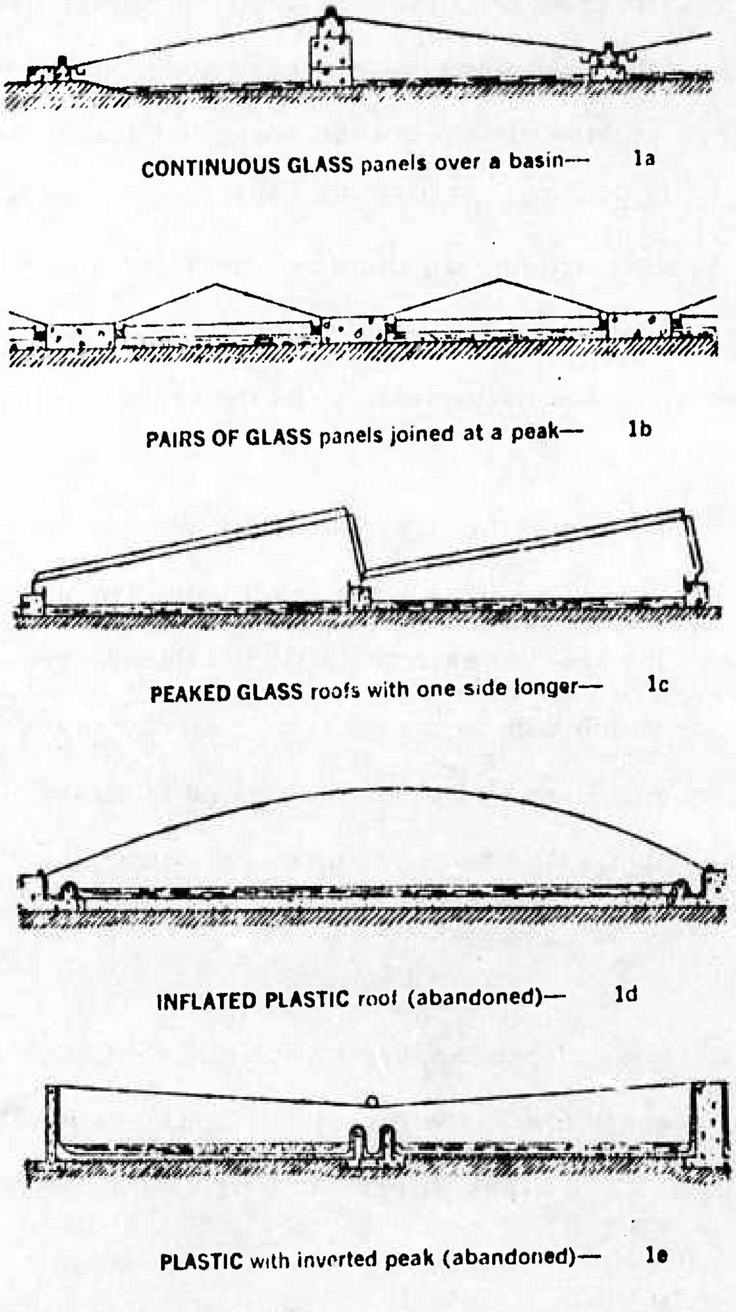


Fig. 150. Schematics of stills with glass and plastic roofs [143].

A large basin under glass panels (Fig. 150, 1a) has been used in a design by Battelle Memorial Institute, for units built at the solar still experimental station at Daytona Beach, Fla., and (with some modifications) at Las Marinas, Spain. The dimensions of the single basin in this design are determined by the projected output. Asphalt matting is used as the basin lining material. The glass roof is peaked with the sloping glass panels supported at their upper and lower sides on prefabricated concrete beams. Distillate is collected in gutters running along the lower edge of each panel. Salt water is admitted periodically to a depth of 4-12 inches; the concentrated brine is evacuated by overflow [143].

An Australian design by Morse and Read provides for individual bays with a peaked glass roof. The width of the basin is limited to about 1 yard. In the latest design, two glass panels are supported along the ground on one side by concrete beams and attached by means of silicon rubber at the peak (Fig. 150-1b). A slope of 15-18$^{\circ}$ is necessary for structural reasons. The basin in this design has a slope of about 1:40, and the brine is subdivided by weirs into a series of cascades so that salt water enters at one end and is continuously withdrawn at the other. The purpose of this is unattended operation for long periods. Similar designs using peaked glass roofs with varying geometry have been erected in Chile, India and the USSR [143].

A design from the University of California at Berkeley is similar to the Australian design in roof geometry, but the peaked glass roofs are oriented across the width of the basin with troughs below the roof edges

run across the still to collection gutters along its length. Several family-size and large units of this design have been installed in some Pacific islands [143].

Three large glass covered stills which have been erected by the Greek government on islands in the Aegean are based on another design (Fig. 150-1c), developed by Anthony and Emmy Delyannis at the Technical University of Athens. Peaked glass roofs with large low-sloping panes on one side and short, steep panes on the other are supported by aluminum alloy structures to provide increased radiation absorption and longer plant life. Several basins, each about 10 ft wide and 65 to 130 ft long, form the still. Butyl rubber sheet is used as the basin lining material. One of these, the plant at Patmos, is the largest solar distillation unit in the world. An improved Patmos design was first used in an experimental still in Gwadar, Pakistan. Roofs of similar geometry have also been adopted in Tunisia and Haiti, using glass on the large side, and brick or concrete for the shorter side.

The usual cover material is glass because of its transmissivity to solar radiation, mechanical strength and low cost. Although transparent plastic foils have also been used in some cases, most of these, except Tedlar*, have insufficient resistance to deterioration by ultraviolet light and weather. In Australia, cheap horticultural-grade glass is used which is available locally

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* Tedlar or PVF(polyvinyl fluoride) - trade name.

at unusually low cost, but in limited lengths. Because of this, the Australian still can hardly be wider than one yard.

The cover material, whether glass or plastic, affects the geometry of the still. With glass, the roof may be peaked or sloped, whereas plastic foil is applied inflated or with stretched-cover designs. The first still erected on the island of Symi, Greece, had an inflated Tedlar cover. Since this design (Fig. 150-ld) exhibited vapor leakage due to the internal pressure and especially poor weather resistance, a second still (Aegina II) was modified by laying steel pipes along the middle of the plastic spans stretched to the plastic cover into an inverted peaked roof (Fig. 150-le). This eliminated the need for internal pressure and only one distillate gutter was necessary to collect condensate dripping from below the pipe. However, this design has also proved to have unsatisfactory resistance to weather. All the plastic stills in Greece have since been abandoned and dismantled.

A blank, polyethylene-film lining material, originally used in Australia, has been abandoned in favor of butyl rubber lining. Elsewhere, black butyl rubber or asphalt is used to line the basin, with the rubber apparently the best for lining. An important innovation in the Australian designs has been the use of silicon rubber sealout throughout, which has proved to be an excellent sealing material.

The characteristics of the world's most important solar distillation plants are given in the following table, covering the period from 1872 to 1970.

| Country | Location | Year Built | * Type | Area $m^2$ | Feed Water | Cover Material | Status |
|---|---|---|---|---|---|---|---|
| Chile | Las Salinas | 1872 | 1c | 4460 | Brackish | Glass | Abandoned |
| USA | Daytona Beach I | 1959 | 1a | 230 | Sea | Glass | Rebuilt |
| USA | Daytona Beach | 1961 | 1d | 215 | Sea | Infl. plastic | Abandoned |
| USA | Daytona Beach II | 1961 | 1a | 245 | Sea | Glass | Abandoned |
| USA | Daytona Beach | 1963 | 1d | 150 | Sea | Infl. plastic | Dismantled |
| Australia | Muresk I | 1963 | 1c | 370 | -- | Glass | Rebuilt |
| Greece | Symi I | 1964 | 1d | 2690 | Sea | Infl. plastic | Rebuilt |
| Greece | Aegina I | 1965 | 1e | 1490 | Sea | V-plastic | Rebuilt |
| Greece | Salamis | 1965 | 1c | 390 | Sea | V-plastic | Abandoned |
| Cape Verde Isl. | Santa Maria | 1965 | 1e | 740 | Sea | Plastic | ? |
| India | Bhavnagar | 1965 | 1b | 380 | Sea | Glass | Operating |
| Pacific Isl. | (several) | 1966 | -- | | Sea | Glass | Operating |
| Australia | Muresk II | 1966 | 1b | 370 | Brackich | Glass | Operating |
| Australia | Coober Pedy | 1966 | 1b | 3160 | Brackish | Glass | Operating |
| Australia | Caiguna | 1966 | 1b | 370 | Brackish | Glass | Operating |
| Australia | Hamelin Pool | 1966 | 1b | 560 | Brackish | Glass | Operating |
| Spain | Las Marinas | 1966 | 1c | 870 | Sea | Glass | Operating |
| Greece | Patmos | 1967 | 1c | 8640 | Sea | Glass | Operating |
| Australia | Griffith | 1967 | 1c | 415 | Brackish | Glass | Operating |
| Tunisia | Chakmou | 1967 | 1c | 440 | Brackish | Glass | Operating |
| West Indies | Petit St. Vincent | 1967 | 1d | 1710 | Sea | Infl. plastic | Operating |
| Greece | Kimolos | 1968 | 1c | 2510 | Sea | Glass | Operating |
| Greece | Aegina II | 1968 | 1c | 1485 | Sea | Plastic | Abandoned |
| Greece | Symi II | 1968 | 1c | 2600 | Sea | Plastic | Dismantled |
| Chile | Quillagua | 1968 | 1b | 100 | — | Glass | Operating |
| Greece | Nisyros | 1969 | 1c | 2045 | Sea | Glass | Operating |
| Mexico | Natividad Island | 1969 | 1c | 950 | Sea | Glass | Operating |
| USSR | Bakharden | 1969 | 1b | 600 | Brackish | Glass | Operating |
| West Indies | Haiti | 1969 | 1c | 225 | Sea | Glass | Operating |
| Pakistan | Gwadar I | 1969 | 1c | 305 | Sea | Glass | Operating |
| Pakistan | Gwadar II | 1970 | 1c | 8130 | Sea | Glass | U/C in 1970 |

* Type of structure indicated in Figure 150.

A typical flow cycle of a solar distillation plant is shown in Fig. 151. Feed water is pumped from the sea or a well into a settling

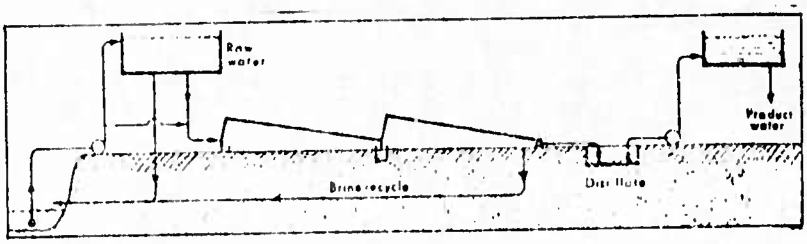



Fig. 151. The flow cycle diagram of a solar distillation plant [143].

basin, or if the raw water is absolutely clear it may be pumped directly to the still. Replenishment of the brine is necessary before its concentration from evaporation is raised to a level at which calcium carbonate and calcium sulfate scaling might occur. When the still is operated on sea water, the brine must be emptied every two or three days in summer and at longer intervals in winter, depending on the operating depth. In most cases, the brine is displaced completely by the salt water, which is fed in over a weir located at the end of the still. An alternative practice in Australia is to continuously feed a predetermined amount of salt water in one end as brine continuously overflows at the other end of the basin. Either complete or continuous brine displacement can create stagnant places in the basin, where salt concentration is built up and scaling may appear. Such deposits absorb solar heat and lower the water temperature. Also, an increase in depth lowers the water temperature, so that the preferred depth for most stills is about 1 inch.

In preventing deposits, the brine is completely emptied from the basin as soon as its concentration approaches the limit of scale formation and replaced by fresh salt water. This operation, developed by Anthony and Emmy Delyannis, has been applied to all glass-covered stills in Greece and complete suppression of deposits has been achieved with continuous operation throughout the year.

It is difficult to determine the cost of desalting units, owing to the different economical and industrial standards of various countries. However, a standardized cost estimating procedure has been adopted at a seminar following the International Solar Energy Conference in Melbourne, Australia, in March 1970, which might lead to comparable figures. For the time being, it can only be said that construction costs of large solar desalting plants fall between 1 and 1.5 dollars per square foot (10.8 to 16.2 dollars per square meter) of evaporating area. Since there are no substantial differences in investment costs between large and small plants, solar desalting is generally economical in small units. With the operating cost of secondary importance, the most important factor to the cost of produced water is the amortization rate. Although there are no records to estimate the life of solar desalting plants, one plant in Las Salinas, Chile has operated continuously for about 40 years. However, the stability of the materials for construction (concrete, glass, butyl rubber sheeting, aluminum alloys, sealants, etc.) is well known from other uses and can be used to set plant lifetime for amortization [143].

In addition to information given in the foregoing table, we may now examine technical data of some solar desalting units and plants designed, tested and in use by various countries, as well as new approaches in solar engineering.

Algeria

As in other countries, first attempts in Algeria were examples of the synthetic experimental methods with equipment designed and constructed on the basis of general ideas without knowing optimal parameters in detail. The results so obtained were then evaluated and design improvements were determined. After World War II, a number of models were developed varying widely in shape, nature, design, and material. All solar engineering studies are conducted by the Hydraulic Service of Algeria, and the Common Organization of the Saharan Regions, with new more systematic searching for basic data, both by experiment and from theoretical considerations and calculations [145].

Australia

Among various institutes, the Mechanical Engineering Division of the Commonwealth Scientific and Industrial Research Organization (CSIRO), Highett, Victoria, is very active in research and development of various solar engineering components, especially experimenting with new

approaches in designing and testing of solar distillation units and plants. Recently, CSIRO conducted an interesting study on the design of a solar still based on nonstationary heat and mass transfer relationships. A graphical solution was developed which expresses the varying heat fluxes as function of the cover temperature. In this way, the output of a solar still under the changing hourly conditions throughout a day can be integrated to give the total output for a 24 hr period. This method may then be used to find the effect on output of changes in various parameters, such as wind velocity, ambient temperature, and the heat loss from the base. The most important variable which the designer of a still can influence is the edge and base loss, together with vapor leakage. This, however, is difficult to measure precisely and is complicated by the fact that it is not always a simple thermal conduction term. For example, in the still design shown in Fig. 152, now being used in Australia,

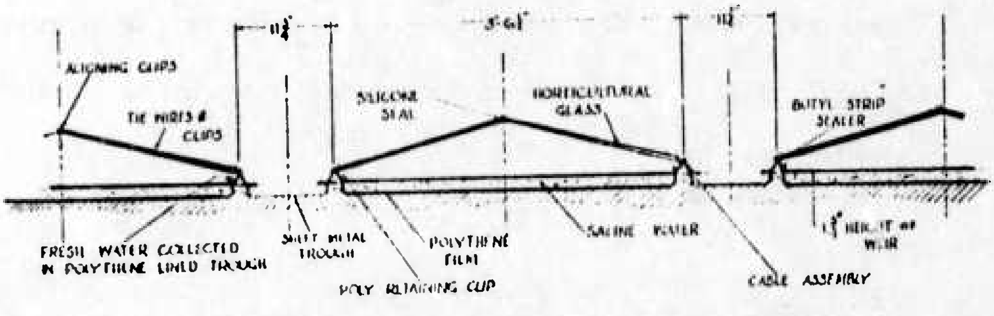
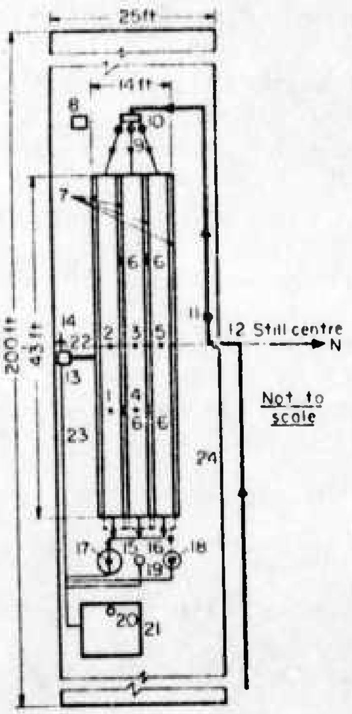



Fig. 152. Cross-section of an experimental solar still, installed at Muresk, Western Australia, having an area of 4500 square feet [147].

the walkways between the individual still sections are made of galvanized iron which has selective radiation absorbing properties and will reach quite high temperatures, resulting in a small temperature difference between the inside and the outside of the still.

In conclusion, the authors Morse and Read claim development of a method for the prediction of solar still performance which is proving to be a useful tool in both understanding the processes which are taking place and in improving the design of hardware. It enables development to proceed on a rational basis by predicting the features from which greatest improvement can be expected. Experiments are still in progress to determine more accurately the values of the parameters applying to a particular design of still, and more work will be needed to verify the validity and check the accuracy of this approach under a wide range of conditions [147].

Researchers at CSIRO have conducted basic work on the digital simulation of transient solar still operation with a mathematical model. The experimental solar still was a CSIRO MK II unit, 500 square feet in area and arranged in three adjacent modules. A schematic diagram of the complete installation with the location of the various instruments is shown in Fig. 153. For a more thorough investigation of the model, a comprehensive experimental program was instituted in conjuction with the formulation of a mathematical model and the development of simulation techniques. The factors measured include: total and diffuse solar radiation intensities, water and glass temperature, brine and distillate flow rates, ambient temperature, wind velocity and direction, relative humidity, and soil temperature beneath the still.




1.
2.
3. } Heat flow meters
4.
5.
6. Soil access holes
7. Galvanized iron walkways
8. Stevenson weather screen
9. Flow stop cocks
10. Flow distributor
11. Pressure reduction valve
12. Mainwater supply
13. Thermocouple switching box
14. Anemometer and vane
15. Brine tank (200 Imp. gal)
16. Distillate tank (100 Imp. gal)
17. Brine dump bucket
18. Distillate dump bucket
19. Diffuse radiation pyranometer
20. Direct radiation pyranometer
21. Instrument housing
22. Thermocouple leads
23. Signal leads
24. Protective fence

Fig. 153. Schematic of complete solar still installation showing location of the various instruments, Australia [148].

Glass and water temperatures, as well as ground temperature, are measured by thermocouples arranged as shown in Fig. 154.

Results from the experimental program have served to establish quantitative agreement between simulated and experimental operation. A qualitative assessment of heat flow within the ground beneath an uninsulated still was made using experimentally recorded ground temperatures. Comparison of the behavior of the mathematical model with the measured

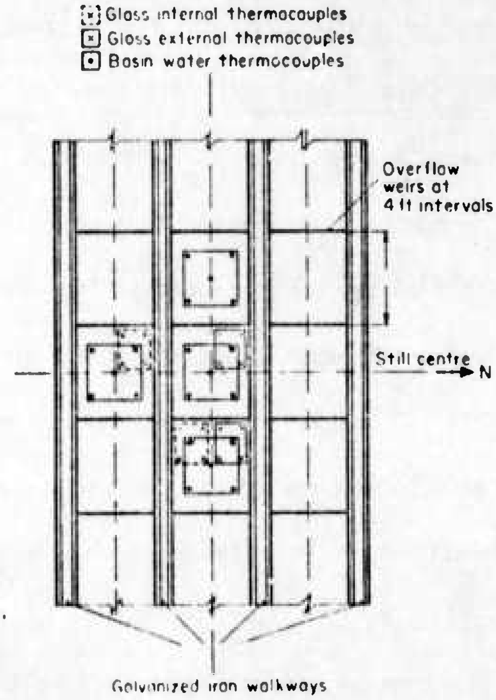



Fig. 154. Deployment of thermocouples in the water and on the cover glass, Australia [148].

performance indicates that the model is predicting with acceptable accuracy the daily output and transient performance of solar stills. The results and trends predicted by the initial investigation into the use of a transient model have also been justified [148].

Recently, Australian researchers conducted an extensive study on exploiting the waste heat from a diesel generating engine. Of the energy supplied to the diesel engine, only about 30 percent is converted into useful work, and the rest is rejected to the atmosphere via the cooling medium, exhaust gases and thermal losses. If water is used as the coolant, 40 percent

of the total energy supplied can be recovered. Places where diesel motor-generator sets are frequently located usually coincide with areas where fresh water is scarce or nonexistent. It is therefore logical that waste heat should be recovered and used to produce fresh water from saline water. Although additional expense is involved, the net result is that the cost of the water produced is generally about half that of water produced from a conventional MK VI solar still. Previous work of Australian workers in this field has been based on adding waste heat to a still externally, while the present investigation is related to the addition of this heat internally.

An experimental system has been set up at Highett, Victoria, using a CSIRO MK VI solar still, a cross section of which is shown in Fig. 155.

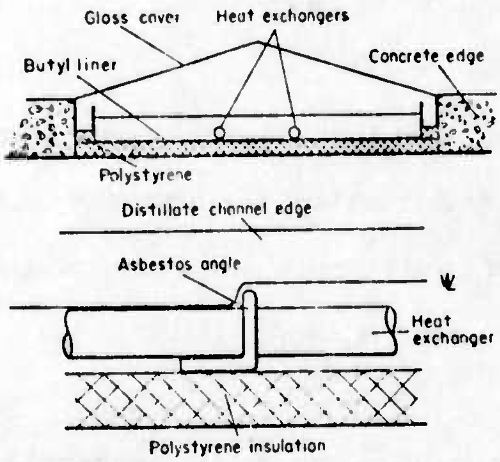



Fig. 155. Cross section of the experimental MK VI solar still, Australia [146].

The heat exchanger for transferring the waste heat to the saline water is a simple straight copper tube. Initial tests have shown that the heat exchanger

worked equally well if the heat flux direction were reversed; it could thus be used, if desired, to extract heat from the saline water and serve a water heating function.

The flow diagram of the waste heat solar still is shown in Fig. 156.

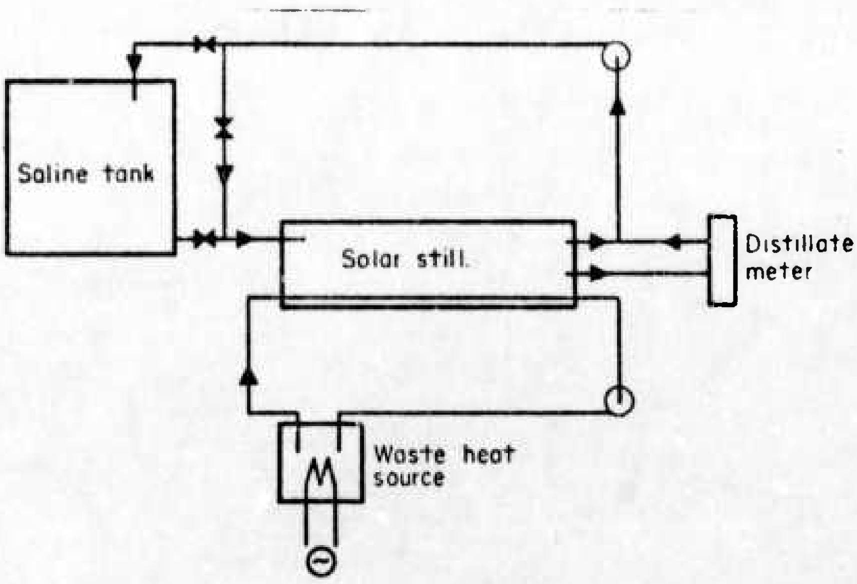



Fig. 156. Flow diagram of experimental waste heat solar still, Australia [146].

The MK VI solar still is 18.5 $m^2$ in area, coupled to a 2720 kg concrete tank insulated on the outside with a polystyrene sheet. A by-pass line is connected across the inlet and outlet saline pipes on the tank. Circulation of saline water is by a submerged centrifugal pump. Future work on this subject will be aimed at finding the optimum relationship between solar still size and saline tank size for a given waste heat input, with respect

to the distilled water and/or hot water produced by the complete system [146].

Recently an experimental small plastic still of approximately 2 square feet has been developed and tested in Sydney (Fig. 157), incorporating several unconventional design features, such as a floating solar absorber to heat a thin layer of water, and a single-sloped roof with a reflecting back wall.

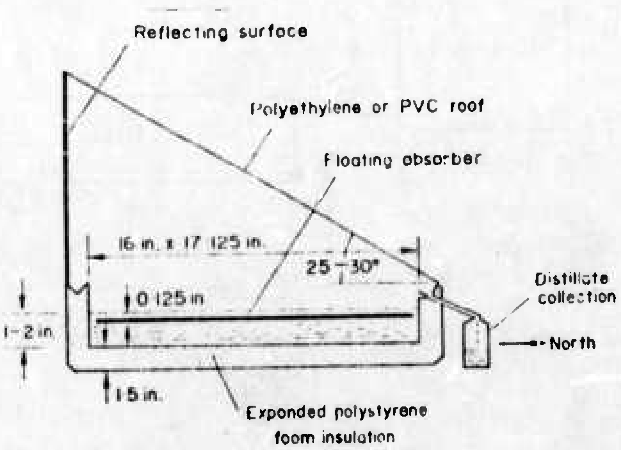



Fig. 157. Cross section of an experimental still with low thermal inertia, Australia [149].

The superior performance of this still, when compared to conventional units, is attributed to its lower thermal inertia, the higher heat input per unit area, and lower heat losses. Factors which are considered important include: the significance of the thermal inertia of the air space between the water and the roof, the need for separate consideration of the water evaporation and condensation rates, and the resulting time delay

between their peaks during the daily cycle. The roof geometry and orientation of the conventional and experimental stills are shown in Fig. 158, in relation to the sun's altitude.

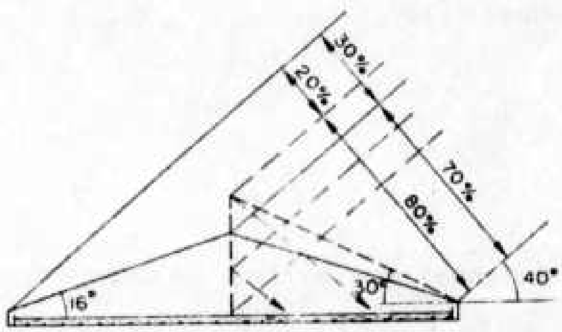



Fig. 158. Oblique radiation incidence on conventional and experimental stills, Australia [149].

The main design features differing from conventional stills were: no black lining of the basin bottom, a black absorber floating on the water surface, a single slope roof (oriented E-W) with only one transparent surface, and the back wall of the canopy lined with reflecting tape [149].

In Australia, solar stills are producing water for motels and small communities on a commercial basis, with several full-size prototypes operating on an experimental basis at field stations since 1963. Before reaching the stage of commercial application, these stills have undergone an extensive period of engineering development and testing [150]. For example, the 38,000-sq-ft Coober Pedy still (1966), erected in northwestern Australia

by the CSIRO, continues to supply all of the freshwater requirements to an important mining community. CSIRO has subsequently erected a 500-sq-ft, experimental still at their station in Griffith, New South Wales. Their new designs are moving in the direction of lightweight packaged units which can be erected by the user [38].

Chile

1972 marked exactly a century since the American engineer Charles Wilson designed and built the world's first industrial solar still at Las Salinas, a small station on the railway from Antofagasta to Bolivia. It had an area of 4700 $m^2$ (4460 $m^2$ according to [143]), and produced 20 $m^3$ of distilled water daily during the summer. It worked from 1872 until 1910, when the first fresh water pipe was completed from the Andes down to Antofagasta [5].

The enclosed picture (Fig. 159) was taken in 1908, after the still had been operating for thirty-six years [97].

In 1956, interest in solar stills was renewed and considerable laboratory research was begun. Various types of solar stills with evaporating trays of wood, metal, cement, plastic, and evaporating cloths of various design have been tested. Tests have been made with glass and plastic covers in the Solar Energy Laboratory of the Federico Santa Maria Technical

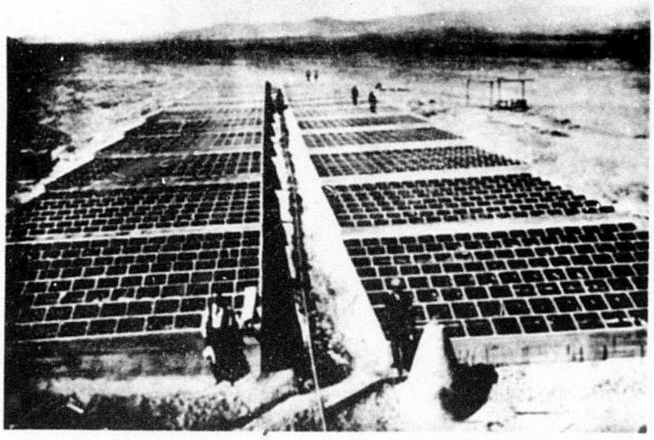


Fig. 159. Solar still at Las Salinas, Chile in 1908 [97].

University, Valparaiso (Fig. 160), and at Quillagua, Atacama Desert (Fig. 161), to verify theoretical predictions of still characteristics under different environmental conditions.

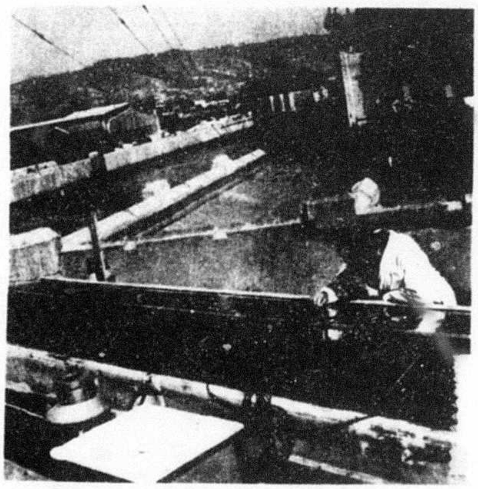


Fig. 160. Solar stills at Santa Maria University, Valparaiso, Chile [5].

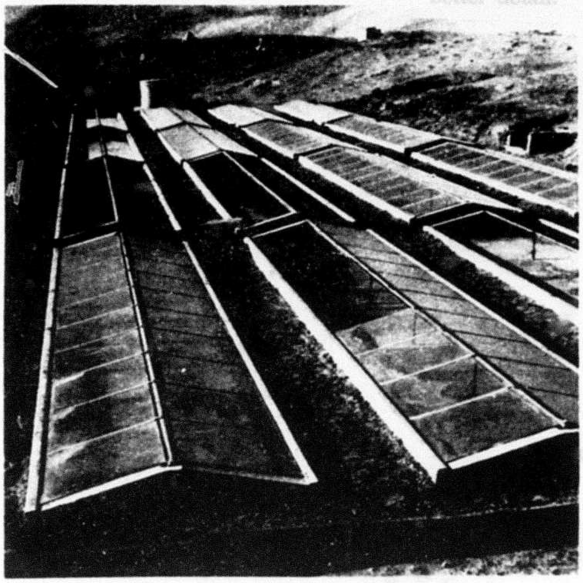


Fig. 161. Solar stills at Quillagua, Atacama Desert, Antofagasta Province, Chile [5].

Construction of these plants started in 1969-1970, with dimensions of 107 $m^2$ and 103 $m^2$ respectively. The first pilot plant for solar distillation built in Quillagua (Fig. 161) is composed of 16 cement trays of 6.06 x 1.10 m internal dimensions (6.65 $m^2$), and the second (Fig. 160) has 62 asbestos-cement trays of 1.90 x 0.88 m internal dimensions (1.67 $m^2$).

Presently, four solar stills of 40, 34, 30 and 20 $m^2$ areas, and with inclined-plane evaporating cloths, are in the construction stage in Santiago. After tests, they will be installed on the roof of workers' houses in the port of Pisagua [5].

Proposals have been made for a Chilean solar facility that would produce not only fresh water but electric power as well. This plant would be built at Maria Elena, a remote area characterized by clear skies but a water supply containing about 4700 parts per million of salt [97]. The dual operation is planned as follows: in the primary circuit, salt water is heated in an inclined plane solar collector at 70° C, passes through an accumulator to separate the air from the water and then to a vacuum evaporator where part of the water evaporates, taking the necessary heat from the rest of the water. In the secondary circuit, the steam thus produced passes through a turbine to generate electric energy, and finally is condensed to provide distilled water. If the salt water intake is at 18° C, the plant will produce an average of 9.5 $m^3$ of distilled water per day and 50 kw of electricity [151].

## France

Since 1968, a flat tilted solar still has been in test by the Solar Laboratory, Marseilles. In order to avoid condensation of the water vapor on the transparent glass cover, a spongy material is bonded to a blackened sheet of aluminum in such a way that the evaporation and subsequent condensation of the water occurs on a rear panel cooled by water or air. It is hoped this will eventually lead to the formation of a multiple-effect still [140].

## Greece

Several experimental solar stills have been in operation since 1964 in Greece. One of the first such projects was a plastic shed-type cover still at Symi (Fig. 162) which provides domestic water and serves as the Solar Stills Experimental Station.

Fig. 162. Solar still at Symi, Greece [97].

The largest of the nine stills is the Patmos (on the island of Patmos) built in 1967 (Fig. 163). This glass-covered still has an aluminum frame, with the base lined with butyl rubber sheeting. It covers an area of 8640 $m^2$, and provides about 26 $m^3$ of fresh water a day [97].

This distillation plant is composed of 71 units, arranged in three groups. The standard size of each unit is 3.29 x 40 m; the basin is formed by concrete strips (8 x 10 m). The Patmos distillation plant has a

Fig. 163. The Patmos solar distillation plant, Greece [152].

shallow basin operating with seawater at a depth of 2 cm to minimize concentration of brine and formation of calcium sulfide crystals. A well close to the shore serves as the intake point for seawater [152].

Greek solar researchers are strong proponents of the creation of an International Experimental Center for Solar Distillation (IECSD), through which it is hoped to achieve uniform coordination of solar research and development with more intensified dissemination of research results obtained by various countries [8].

India

The National Physical Laboratory of India and the Central Scientific Instruments Organization, both of New Delhi, have been active in research and design of solar stills to be used in the semiarid region of Rajasthan, where the water situation is extremely acute. This region is in great need of demineralization of saline and brackish waters, since much of the water-bearing strata has a very high mineral content unfit for drinking or irrigation. Conditions here are very favorable for exploiting solar energy for distillation, since the region has bright sunshine for the most of the year and the sun is at a high angle.

A solar still, designed by the above organizations (Fig. 164) was constructed from wood on a masonry platform. The metal basin, measuring 8 ft x 3 ft 8 in and a depth of 1.5 inches, is of galvanized sheet coated with black bituminous paint. Two inches thick sawdust serves as the tray insulation. One filling of the tray with water can last about 3-4 days. The output of this still is about 2.8 liters of fresh water per square meter per day [153].

The Central Salt and Marine Chemical Research Institute (CSMCRI) in Bhavnager has concluded the final design of a solar still, using aluminum components and black polyethylene film for the basin lining. It has external dimensions of 2.36 x 1.22 m with a double-sloped glass cover

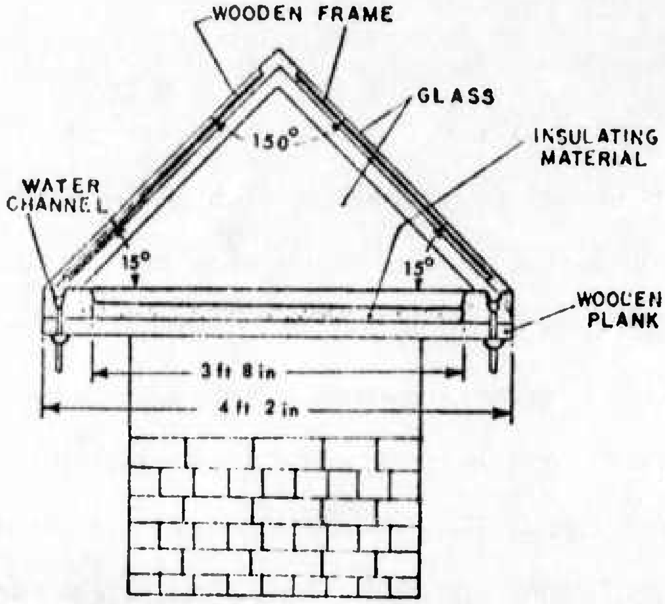



Fig. 164. Cross section of a solar still, India [153].

at an angle of $20^{\circ}$. The capacity of this still ranges between 5 and 7 liters of distilled water per day (Fig. 165). Such units are already in use to supply distilled water for laboratory work and a number of other installations [154].

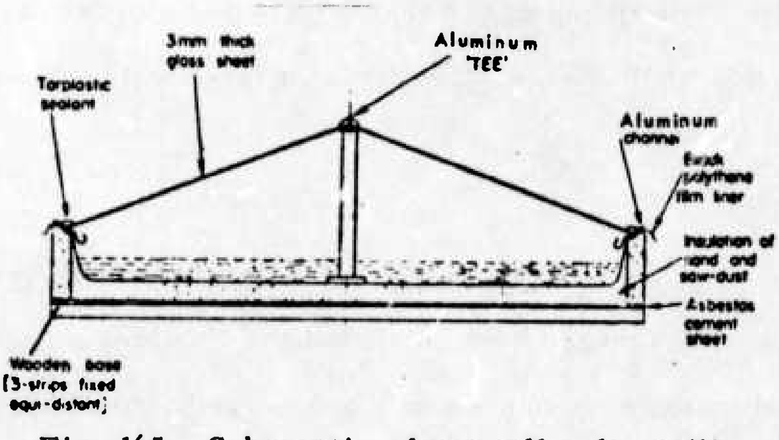



Fig. 165. Schematic of a small solar still, India [154].

Japan

One remarkable result of solar still research is the "earth-water" still, invented by Kobyashi during the second World War for the production of water on the dry islands of the Pacific. Little came of the idea at that time, but in recent years Japan has developed a variety of small glass and metal stills capable of producing fresh water, not from salt water, but from ground water. A cone-shaped hole is dug in the ground and a container placed at the center of the depression. Next a sheet of clear plastic is laid over the hole and the edges covered with earth. The plastic is pushed down in the center and weighted with a rock, forming a crude plastic still with sloping sides terminating just above the collector. Heat generated under the plastic evaporates moisture in the earth, and this condenses on the underside of the plastic and drips into the collector. Properly set up, the earth-water still will produce about a quart of water a day from about one square yard of earth. The earth-water still has some potential uses in agriculture, land reclamation (swamp drainage), camping, as part of a survival kit, and other outdoor activities. For example, Ray Jackson and Cornelius van Bavel of the U. S. Department of Agriculture have independently developed a similar though much simpler survival still for use in the desert [97].

USA

The design parameters of solar stills have been under study by a number of American scientists and institutions. During World War II, experiments were conducted by Dr. Maria Telkes on an inflatable floating solar still for possible use on life rafts. This unit consisted of a transparent plastic envelope containing a black absorbent pad. The plastic envelope was spherical on top and conical on the bottom, designed to float with the conical end submerged. Sea water flowing into the top saturated the felt pad, and sunlight passing through the plastic envelope would be absorbed in the pad and cause evaporation of the water. The moisture of the warmed air would be partially condensed on the plastic surface of the lower conical section, since it was cooled by the sea.

Following her wartime experiments on the floating stills, Dr. Telkes designed and tested a unit of about 4 x 50 feet in Cohasset, Massachusetts and as consultant to the University of California, produced a preliminary design for the first solar still units installed in Richmond, California. These were five units of 4 x 8 ft arranged as shown in Fig. 166. The trays were of wood, insulated on the underside and covered with glass hoods as detailed in Fig. 167 [18].

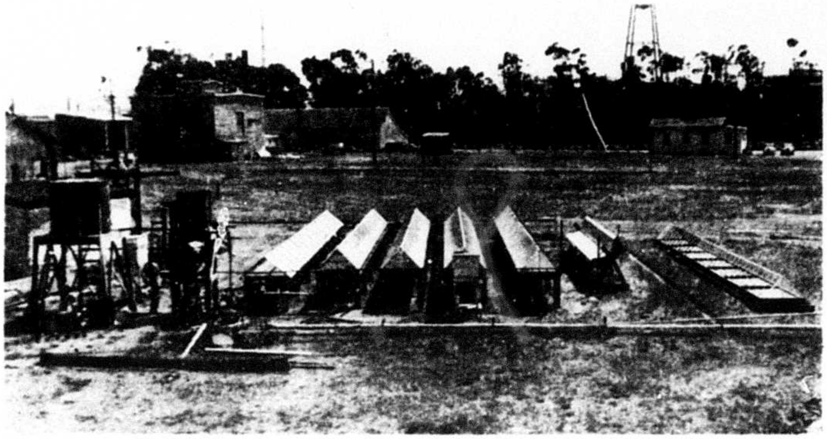


Fig. 166. General view of the experimental solar distillation plant, University of California, Richmond, California [18].

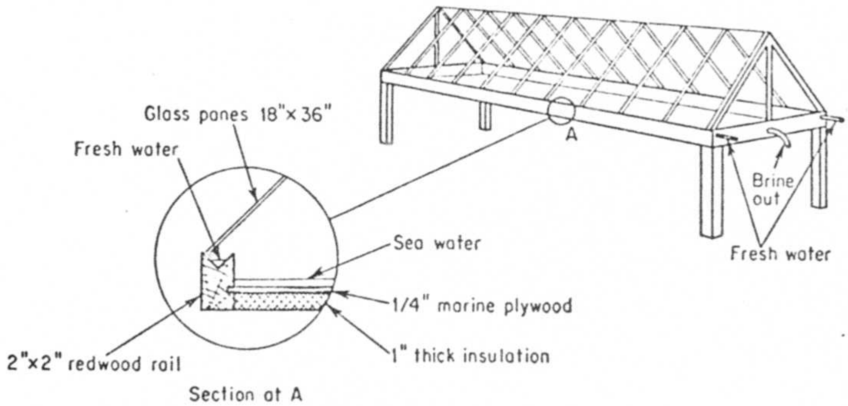



Fig. 167. Details of experimental solar still, Richmond, California [18].

Since 1953 the Office of Saline Water has had projects under way in solar distillation, carried out primarily by means of contracts with R & D organizations. Although efforts to produce fresh water by some means of solar distillation have been proceeding for many years, the number of solar stills actually produced for use has been rather small.

One of the first solar investigations under the Saline Water Conversion Program was conducted by Dr. George Löf who made an engineering survey and evaluation of possible methods for converting saline water by use of solar energy.

The Department of the Interior established a solar distillation research station at Daytona Beach, Florida to provide a field installation for integrated solar still development programs where small pilot plants or equipment prototypes of various designs could be installed, operated, and further developed. The station has been operated through a research and development contract with Battelle Institute. The experimental work at Daytona Beach on the use of plastics confirms the promise of the technical and economic feasibility of these types of solar stills. Beginning in 1959, further developments of plastic cover basin stills were also undertaken by the DuPont Company at a site near Miami, Florida. On the basis of various experimental results, it was concluded that basin-type stills built directly on dry ground are the only presently practical type for large capacity solar stills [115].

Small domestic solar stills are now being manufactured and sold by the Sunwater Company of San Diego. Constructed of concrete in modular units (3 x 10 ft), these glass covered, shallow pan stills are being installed in an increasing number of homes and resorts along the Pacific coast of California and Mexico. These stills are provided with automatic water feed devices, and have a capacity of 2 to 200 gallons of fresh water per day [38, 97].

Further enumeration of all the U.S. scientists and institutions active in the research and development of solar stills is beyond the scope of this study.

## USSR

The Physicotechnical Institute of the Uzbek Academy of Sciences has designed a sloped-step solar distiller with an area of 100 $m^2$; for comparative study this still was combined with another greenhouse-type solar still having an area of 600 $m^2$. This complex has been tested at the Shafrikan State Farm, Bukhara Oblast. The still (Fig. 168), with a total area of 700 $m^2$ and an output capacity of 150 liters per square meter or 700-750 $m^3$ annually, is composed of 45 independent sections, of which 6 sections (16.5 $m^2$ each) are of the sloped-step type. Each section is 1.30 m wide and 12.5 m long, with a separation of 30 cm between sections, and 1.85 m between groups of sections. Reinforced concrete pans have been positioned at $30^{\circ}$ angle from

the horizontal, and covered with glass 1.30 x 1, 1.30 x 0.5 and 1.30 x 0.65 m in size.

Filling of trays with salt water is done from tanks fixed on the upper portions of each section, with about 60 $m^3$ of water needed for filling all sections. In the summer, trays are refilled within 3 to 5 days, and for the rest of the year within 10 to 20 days. The testing area is paved and collects rainwater for the tank reservoir.

Data obtained during tests in the summer of 1970 indicate that the sloped-steps solar still is 30-40 percent better than the greenhouse-type still. Based on these results, the sloped-step solar still is considered as the most efficient unit, and as such has been approved by the government for serial production. (Source [157] gives slightly different dimensions for the above solar still [139, 156, 157]).

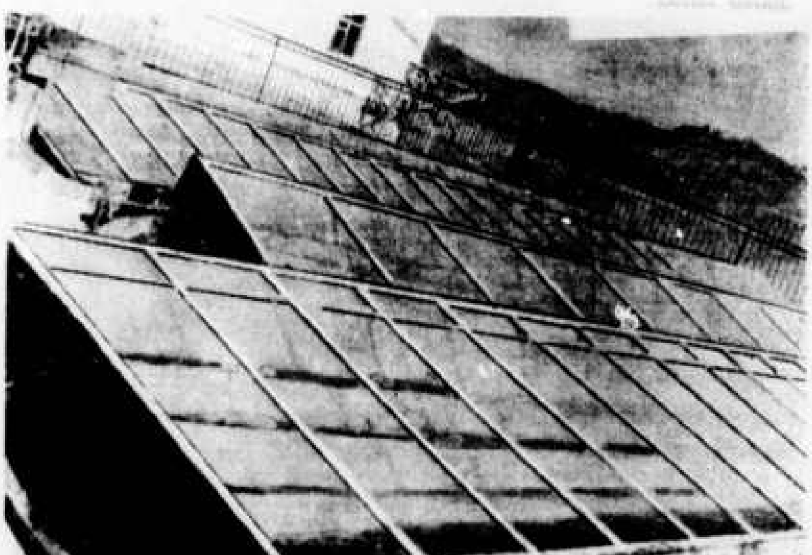


Fig. 168. Partial view of the sloped-step solar still at Shafrikan State Farm, USSR [139].

The Physicotechnical Institute of the Turkmen Academy of Sciences recently designed and is now testing a solar still with an estimated capacity of 2400 $m^3$ distillate annually [32].

Besides conventional solar stills operating by direct solar radiation, the Solar Laboratory of the Krzhizhanovskiy Power Institute, Moscow has designed and tested a three-stage regenerative type still in Tashkent (Fig. 169). The steam for this was generated from a solar boiler

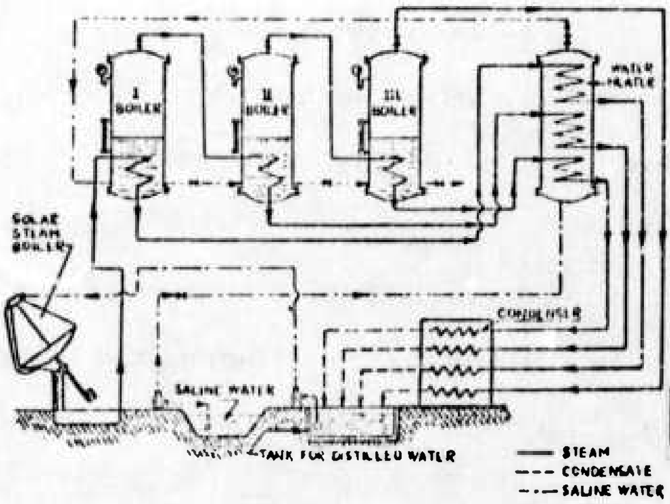





Fig. 169. Tashkent three-stage regenerative type distillation plant, USSR [142].

placed in the focus of a parabolic mirror 10 m in diameter. The boiler produces about 50-60 kg of steam per hour at a pressure of about 6 atm. In the month of June (the highest solar radiation) this still has produced about one ton of distillate a day, and the efficiency of the boiler has been rated at 60 percent.

The steam is fed to a turbine to generate electricity with a counterpressure of 2-3 atm, and the used steam is switched over to the condenser. The steam could also be used in a condensation type turbine and use the generated electricity for water distillation by means of electrodialysis [142].

Desalting schemes involving generation of electric energy have until recently been generally rejected by experts. However, it should be noted that Baum [142] has concluded that such a scheme is feasible, and has undertaken a detailed study toward its application in desalting of brackish water [145].

There are several other countries engaged in research and development of solar stills, such as England, Iran, Israel, Italy, Kenya, Norway, Spain, Trinidad, Turkey and others.

In conclusion, there appears to be a large and growing market for small solar stills in the more remote and technically less developed areas of the world. The main tasks remaining in this field are:

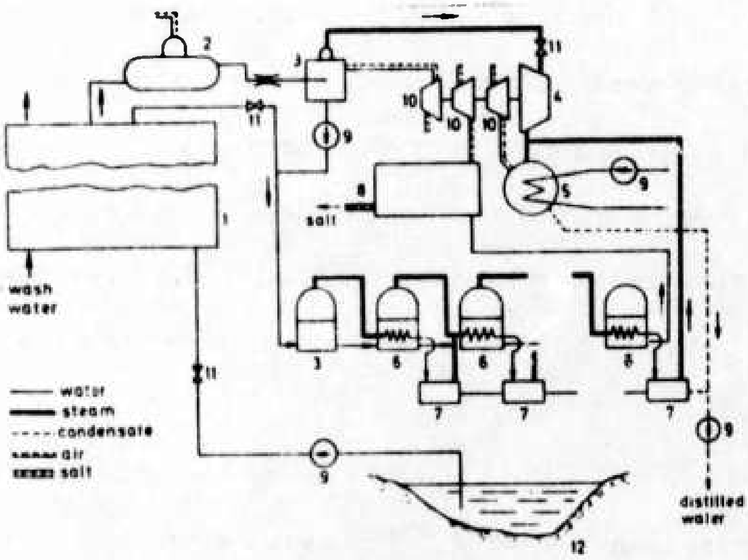
o to develop new models of solar stills and increase the water production per unit surface;

o to check the use of new construction materials and lower production costs;

o to design solar stills for the production of large amounts of fresh water.

## 2. Salt Extraction

While solar distillation plants play an increasingly important part in providing desalted water, they can be equally important in the field of salt recovery. While there are large deposits of rock salt obtained by mining or pumping, it is often more economical to obtain it from sea water by evaporation or from salt ponds through a desalting plant [20]. Such a desalting plan was proposed at the First International Symposium on Water Desalination held in 1955 in Washington (Fig. 170). Studies made in Israel,




1) Solar Pond
2) Acumulator
3) Flash-vaporizer
4) Steam-turbine
5) Condenser
6) Vaporizer-condenser
7) Vaporizer-box
8) Vacuum cristallizer
9) Circulation pump
10) Vacuum pump
11) Regulation valve
12) Salt water source

Fig. 170. Scheme of a proposed plant for distillation of saline water and production of pure salt from solar ponds [25].

Chile, and Australia show that technical difficulties in building industrial plants of such a type are not too great. It only remains to determine the most suitable size of the pond which would serve as a prototype. Some researchers have concluded that the ideal pond size would be 1.2 $km^2$, which still has to be confirmed by further studies. In general, the selection of site will depend largely on factors such as water availability, water transportation cost, and electrical power transmission in the event that plant will not produce its own electricity.

India is one of the major salt producers in the world; because of favorable weather conditions, salt production there is accomplished primarily by solar evaporation in open pans or ponds. These salt-producing facilities often are faced with a shortage of drinking water, in which case solar stills offer a solution to the problem. Solar stills have been provided by certain salt works, designed on the basis of previous experience.

For the recovery of one ton of salt, about 45,000 liters of water must be evaporated. The evaporation rate in open pans depends on the temperature and humidity of ambient air and the wind velocity. In general, the degree of evaporation changes the concentration of sea water from 3.5° Bé* to 23° Bé while it is being circulated in the reservoirs (density rising from 3.5° Bé to 6° Bé), and in three condenser stages (density rising from 6° to 10°,

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* Bé - Baume hydrometer scale, in which 0° is the point to which a Baume rational hydrometer sinks in water, and 10° is the point to which it sinks in a 10% solution of sodium chloride, both liquids being at 12.5° C.

$10^\circ$ to $14^\circ$, and $14^\circ$ to $23^\circ$ Bé). Brine which has been condensed to $23^\circ$ Bé is then fed to crystallizers where, after further evaporation, salt crystallizes out and is harvested. Unless there is interest in recovering gypsum, which separates after the brine has been concentrated to $14^\circ$ Bé, the process prior to crystallization (about 85 percent of the entire salt works) involves very little human activity. Therefore, the addition of a permanent cover to collect the evaporated water, which will otherwise be lost to the atmosphere, would in no way obstruct the salt making operation. The evaporation rate decreases as the brine density increases. Reported values indicate an evaporation rate of 13/32 inch/day for $3^\circ$ Bé; and 9/32 inch/day for brine of $10^\circ$ Bé. This means that the covers (glass or plastic) used for the recovery of water should preferably be used in reservoirs or in first stage condensers. The rate of brine evaporation with cover (as in solar stills) will be smaller than with open evaporation. Hence in the case of covered evaporation, the productivity or evaporation rate increases with increasing brine temperature. Experiments have been started on this and other problems at the Central Salt and Marine Chemical Research Institute, Bhavnagar, India, to resolve contradictory results between those of Indian researchers and the Leslie Salt Co. of San Francisco [154].

The Leslie Salt Company on San Francisco Bay operates the world's largest solar-powered evaporating plant for the extraction of ocean salt, comprising a coastal strip 40 miles long with 29,000 acres of ponds producing about 900,000 tons of salt per year, as well as a considerable

tonnage of brine concentrates. The crystallization season begins here in April. Because ocean water contains other salts besides sodium chloride, these have to be removed by crystallization, settling or chemical extraction. Calcium sulfate, for example, is the first to be crystallized and allowed to settle and at this point in the process the salt content of the water has actually been concentrated from the original 3 percent to 25 percent.

This saturated solution is then pumped into a watertight, clay-bottomed basin and exposed to the sun. Calcium carbonate, magnesium chloride and certain potassium salts are extracted during this phase by chemical and other means. When the solar evaporation process is completed, the resulting salt is 99 percent pure sodium chloride, with only very slight traces of other salts. An additional vacuum process refines it still further, so that the product put on the market for human consumption is 99.9 percent pure.

From April to October the salt "grows" in the crystallization basins, reaching a depth of from 4 to 6 inches by "harvest time," which runs from the end of September to the middle of December. The harvesting employs power scoops on caterpillar treads, which load the salt on two-ton gondolas at the rate of about 25 tons of salt per hour. The 6-foot-wide shovels are adjusted and operated so that they harvest the salt without disturbing the sand or silt underneath. After transport from the bay area to the Leslie plant

inland, the crude salt is again chemically treated in huge water tanks. The concentrated solution is boiled in special tanks about 20 feet high, after which it crystallizes once more, the salt being conveyed through rotary kilns until completely dry. From there to the packaging room the remainder of the work is performed by automatic machinery, and eventually the transformed ocean salt reaches its ultimate consumer [20].

When salt is extracted in this manner by solar energy, the efficiency of the process and the quality of the product depends on a number of factors other than the solar heat itself, such as the flatness of the ocean bed, the correct amount of evaporation during the crystallization period, the average daily precipitation, and even the intensity of summer rainfall. Because these conditions are found in practically ideal combination in the San Francisco Bay area, nearby all of the salt produced in the United States by the solar energy method is extracted here. The seawater of the ocean is either pumped into the evaporation basins or allowed to flow in by gravity.

In general, there are nine concentrating stages, one crystallizing pond for sodium chloride, and a final evaporating pond for the bitterns drained from the crystallizing pond. Calcium sulfate precipitates in the seventh pond. The crystallizing pond collects 75 percent of the sodium chloride at a purity of 98 percent. The bitterns are drained from the crystallizing pond at $29^{\circ}$ Bé (specific gravity 1.25) and are held in the final bittern pond until it reaches $31^{\circ}$ Bé (specific gravity 1.27), at which time they are removed

and sold for chemical recovery of magnesium and bromine. The sodium chloride from the crystallizing pond is washed and processed to purities of 99.9 percent for food uses and 99.4 percent for chemical and other uses.

The use of solar energy for the evaporation of brines as described above has been analyzed in detail by several scientists. These experiments used a series of evaporating tanks 1.2 m in diameter, mirror lined to simulate large ponds, and well insulated on sides and bottom to further ensure similitude. From an analytical study, it appeared that considerable heat would be lost from the ponds through reradiation from the white salt crystals covering the bottom. Some researchers proposed the use of dyes as a means of causing solar radiation to be absorbed directly by the water (or brine) rather than being first absorbed by the coating on the bottom of the pond and transferred to the water by free convection. Their experiments showed that the addition of dyes would permit practically complete absorption of solar energy in shallow pans. This method was applied to the ponds of the Dead Sea Potash Works, where it resulted in a 40 percent increase in production [18].

Since 1958 considerable work has been done in this field by various institutions and individual researchers in several countries [20].

F. Agricultural Applications

Agricultural production is one application in which solar energy is converted into chemical energy through agricultural products and in turn through livestock. Important factors for the agricultural use of solar energy may be determined by studying the geographic and seasonal distribution of solar radiation and micrometeorology. The latter is concerned with investigations of the intensity of solar radiation on slopes as well as on leaves, temperature variations in irrigation water, temperature control of soils and greenhouses, the acceleration of melting snow, etc.

Agroclimatological methods for estimating rice production have been studied widely, especially in Japan, using a climatological productive index by measuring sunshine and average atmospheric temperatures.

An extensive research effort has been conducted on water warming ponds for agricultural purposes, i.e., to warm the cool irrigation water. The temperature rise and heat absorption coefficient of a pond were found to be important factors relating to the intensity of solar radiation, resulting in the heat exchange between the water surface and contacting air layer being critical.

The light distribution and photosynthesis in canopies of randomly dispersed foliage area have been analyzed by various researchers, suggesting that the variation of gross photosynthesis with light incidence and

scattered rays are variables of leaf inclination in relation to the sun. Other works on corn and tobacco leaves are also related to these studies.

Algae production by means of a solar-exposed open cycle has already been commercialized. Problems encountered in an earlier stage of the research, i.e., the repugnant algae smell and the difficulty of digesting it have been overcome by rapid spray drying in a vacuum and by keeping the product at a temperature below $5^{o}$ C.

Other promising fields of research and application in agriculture are mulching in fruit orchards to reduce evaporation and prevent the growth of weeds, inexpensive greenhouses with plastic film, snow melting experiments by the use of calcium silicate or dusting black powder, and the design of a solarometer for measurement of photosynthetically active radiation, as well as other instruments [101].

1. Greenhousing

Arid regions sometimes have substantial amounts of brackish water (sea water, pond water, or ground water), while the fresh water is usually limited seasonally or very scarce. As a consequence, it is sometimes very difficult to raise certain crops that require even higher water quality than living beings. Furthermore, many areas that are termed arid enjoy exceptional sunlight conditions and very clear skies, making the atmosphere extremely dry. The latter factor greatly restricts the opportunities for growing plants,

since the water provided for them is rapidly lost by evaporation.

The problem assumes a different aspect when the plants are cultivated not in the open air, but in relatively closed environments, permitting access of light and sharply restricting the evaporation of water. There has been an increased world-wide interest in cultivation in closed spaces, commonly known as greenhouses.

A review of the various factors that affect plant life in greenhouses would have to include illumination, temperature, water requirements, ambient atmosphere, soil type and pest control. For present purposes the discussion is limited to the first two factors.

Illumination

Solar radiation acts directly on plants by controlling the phenomena of chlorophyll assimilation and transpiration. It also affects the air and soil temperature, and the relative humidity of the air. In discussing the action of light, account must be made for differences between the intensity received (which is often extremely great) and the distribution of the hours of sunshine according to season and latitude.

The illumination of the plants in a greenhouse can be controlled by means of panels that reflect the solar radiation (aluminum foil panels or

panels painted white). In many cases, it is desirable to increase diffuse light by means of interior walls which also reflect the solar radiation.

The effect of temperature to a certain extent is connected with illumination, since the heating of the greenhouse is largely due to the solar radiation. The optimum temperatures are often 20-25$^{\circ}$ C; the vegetative phenomena cease when 40$^{\circ}$ C is approached, hence excessive heating of the plants should be avoided. The greenhouse cover ratio of the growing zones must be adequate for this purpose.

## Temperature

Temperature control depends on the dimensions of the building, and the relative area of the outside walls is obviously very important. However, they can easily be covered with selective linings to prevent them from becoming heated during the day and to obtain substantial cooling at night. The nature of the soil and of the adjacent vegetation also plays an important role. In general, the daily temperature range is less important, but the average temperature of the greenhouse should not greatly exceed the average outside temperature. In regions of the Sahara type, the day-night temperature difference may exceed 15$^{\circ}$ C.

To obtain high crop yields in greenhousing, one must realize a balanced correlation among the various factors, particularly light, temperature and humidity, which conditions may differ considerably according

to the plant species being cultivated. Since the construction of a greenhouse is relatively costly, the crops grown in them must necessarily be intensive and be organized rationally from the human point of view [77].

One current theory asserts that the opacity of the glass to long-wave radiation has little or no effect on trapping of solar energy. To prove this point, two small enclosures with transparent covers, one of glass and the other of rock salt crystal, were constructed. Rock salt transmits long-wave energy as well as short-wave energy and has a transmissivity nearly the same as glass. These enclosures were placed in the sun and it was found that thermometers in the two enclosures indicated the same temperatures. Since any long-wave energy emitted as radiation could pass through the rock salt but not through the glass cover, it follows that the equivalence of temperatures within the two enclosures showed such radiation to be of very small magnitude. The reason for the trapping of the energy must then lie in the low rate of heat flow by convection from the warm surface inside the greenhouse to the glass hood. This explanation is credible if it is recalled that the presence of the enclosure limits the interior air circulation to that from free convection, and that this is an extremely poor means of heat transfer. In general, the greenhouse effect occurs in any enclosure which has a transparent cover, and is the basis on which all low-temperature solar collectors are designed [18].

At the Mont-Louis Laboratory of Solar Energy a greenhouse has been designed and built based on simple method of growing plants with the added feature of production of pure water from brackish water. This greenhouse (Fig. 171 and 172) consists of the following components: an

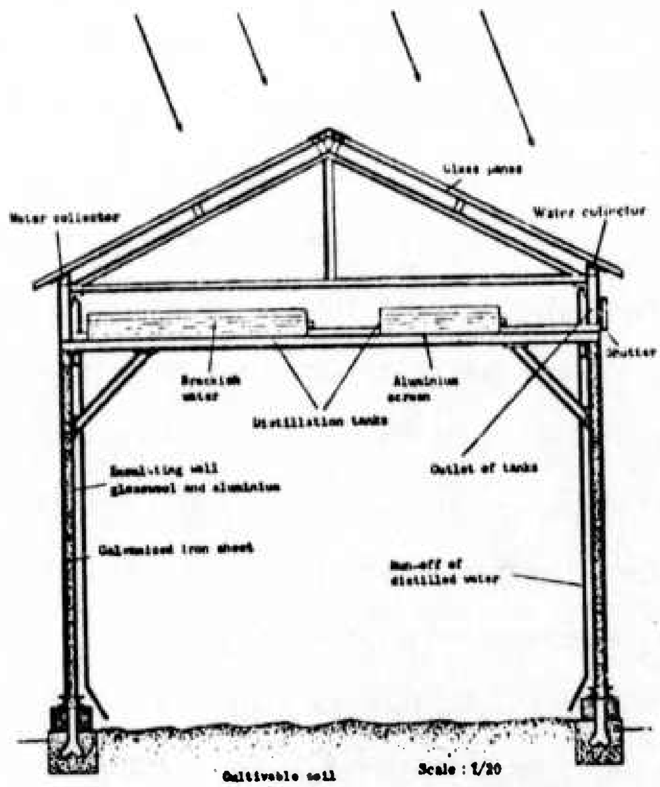


Fig. 171. Cross-section of a greenhouse permitting simultaneous distillation of brackish water and air conditioning in arid regions, France [77].

impermeable base covered with a growing medium; pans, located at ceiling level, containing the brackish water to be distilled; a roof formed of inclined elements with glass or plastic transparent to solar radiation; and walls which provide appropriate thermal insulation and reflect the radiation.

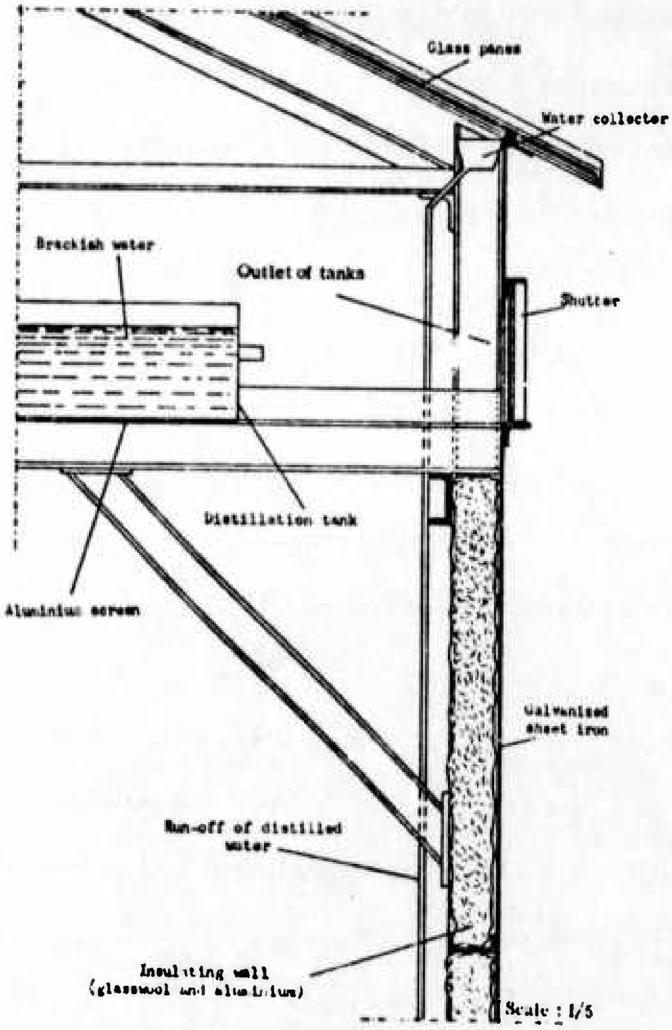


Fig. 172. Detail of greenhouse with arrangement of water collectors and the structure of the lateral walls [77].

The brackish water in the pans is evaporated by solar radiation, then condensed on the inclined transparent roof and runs off to ground level. Sunlight is admitted only partially into the lower part below the pans, and the hot air under the glazed roof does not descend to the level of the plants, owing to its low density. Evaporation of water in the pans also limits the temperature

level under the roof. The temperature gradient in an upward direction is accompanied by a gradient of relative humidity, as the air saturated with water vapor (which is less dense than the dry and superheated air) tends to remain under the glazing.

The transparency of glass or plastic films to solar radiation is about the same (90 percent). However, plastic is more transparent in the ultraviolet, which is important for the flowering of plants. In various regions of the infrared, very thin films of plastic have numerous absorption bands separated by transparent zones. Glass is transparent up to about 2.7 microns, dropping to completely opaque beyond 4.5 microns. It also displays a well-marked reflection band of 9.5 microns. In the case of very thin plastic covers, part of the direct radiation from the greenhouse (pans and growing plants) will exit through the plastic, whereas it is completely blocked in the case of glass [77].

There are many countries with accelerated research and development programs for the construction of solar greenhouses in order to increase the production of various vegetables, fruits, and flowers year-round. In general, the principles of solar greenhousing are standard with some geometry variation in conformity with the geographic location, local need, and available material. However, the abundance of designs and variety of shapes and capacities preclude more detailed tabulation of all greenhouses, with the exception of those outlined below.

Canadian scientists are conducting research in the design and construction of industrial type greenhouses in Quebec Province. Experimental tests during the winter 1971-1972 established favorable economic backing for mass production. It has been estimated that about 13 to 50 percent of the daily solar radiation will be adequate for heating of a moderate size greenhouse. Fig. 173 is a section of the experimental greenhouse (area 725 $m^2$) with combined heating by solar energy and a central heating system [158].

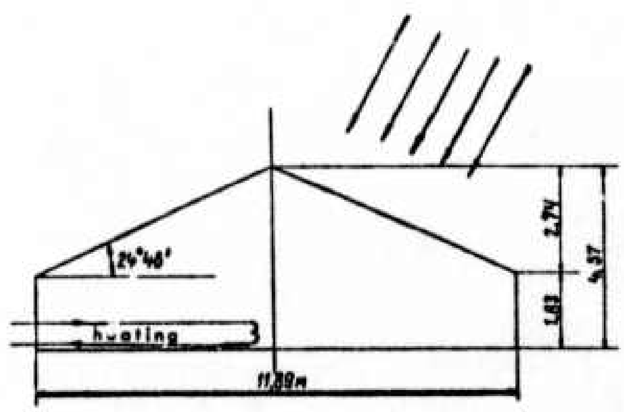

Fig. 173. Sketch of an experimental greenhouse, Canada (dimensions in m) [158].

Bulgarians are notably skilled in agriculture, especially in gardening. To illustrate their advancement in greenhouse farming, Fig. 174 shows the enormous size of one among many state greenhouse complexes. This farm is located near the town of Pazardzik, in the Maritsa River valley [159].

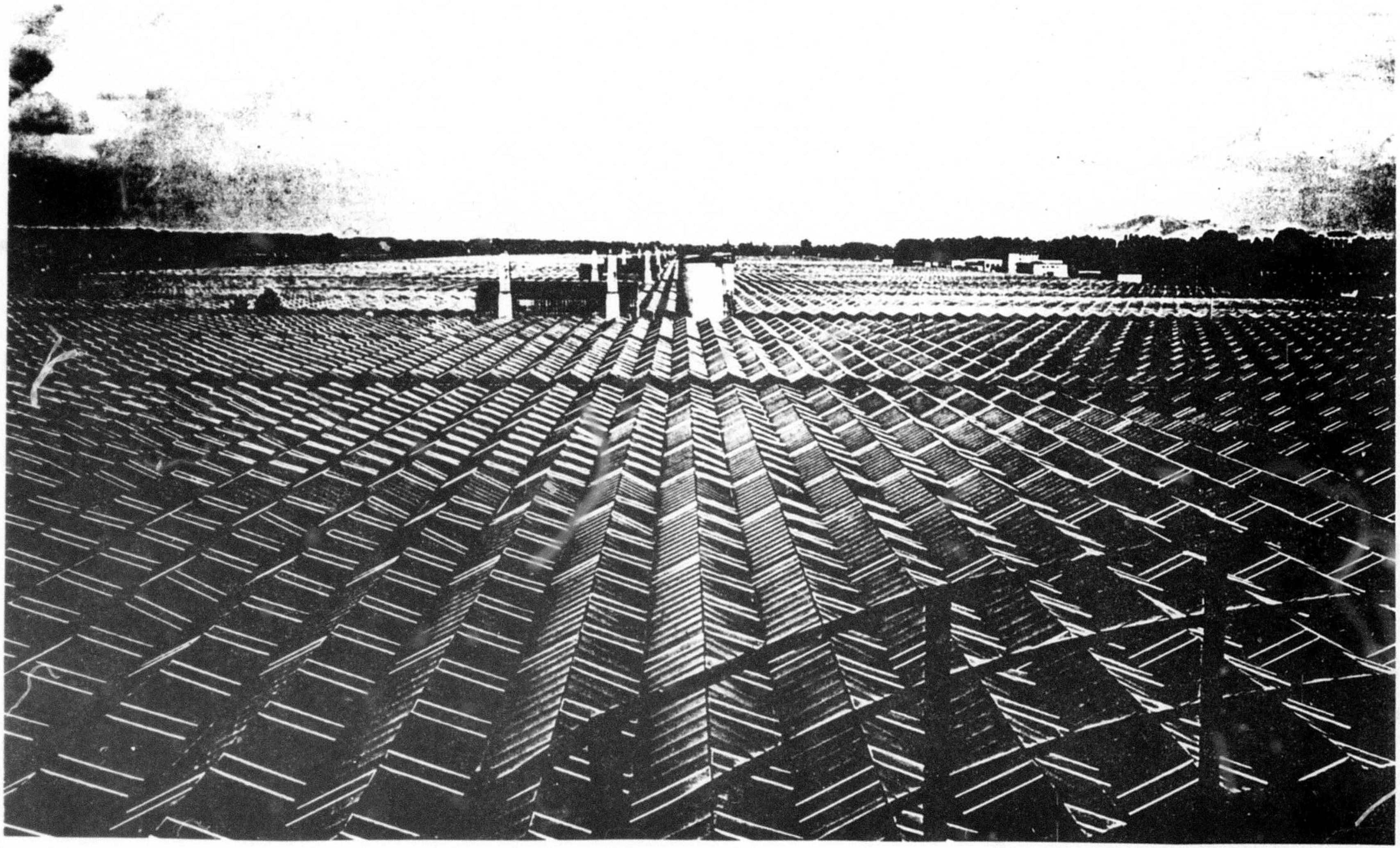

Fig. 174. The solar greenhouse complex near Pazardzik, Bulgaria [159].

In the Soviet Union many collective and state farms are building semicylindrical greenhouses (Fig. 175) made of metal pipe frames and covered by polyethylene film. In 1970, from an experimental semicylindrical greenhouse (40 m long, 5 m wide at the base, with 2.5 m radius) favorable data was obtained regarding the amount of incident solar energy at different geographic orientations, as well as daily declination of the sun and the values of direct and dispersed radiation [160].

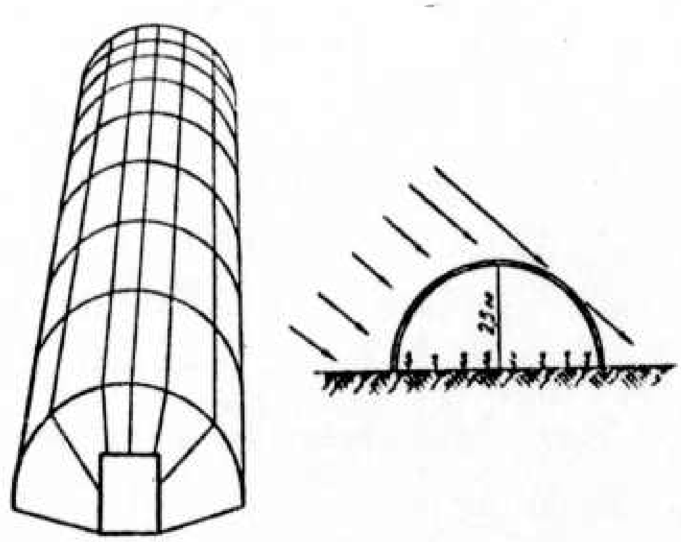

Fig. 175. Schematic of a semicylindrical greenhouse, USSR [160].

During 1967-1972 the Physicotechnical Institute of the Uzbek Academy of Sciences jointly with the State Pedagogical Institute, Karshi, Uzbek SSR, conducted extensive research on temperature regimes in a semicylindrical greenhouse both with and without solar heat storage. The form and dimensions of this greenhouse (Fig. 176) are the same of that in Fig. 175, except for the added solar heat storage compartment filled with

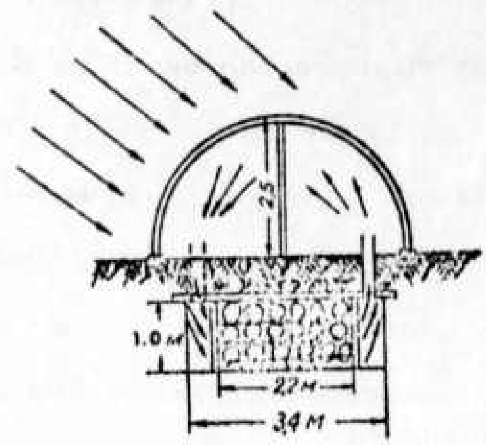


Fig. 176. Schematic of a semicylindrical greenhouse with solar heat storage, USSR [161].

pebbles (10-15 cm in diameter) as heat accumulators with specific weight of 2500 $kg/m^3$ and a thermal capacity of 0.22 kkal/kg/degree. The heat storage compartment has a total volume of 88 $m^3$ and is about 55% filled with pebbles. The greenhouse was covered by a double polyethylene film (350 $m^2$) over a growing area of 200 $m^2$, with inside solar radiation capacity ranging between 490,000 and 500,000 kkal/day.

From several experiments it was established that in a greenhouse without solar heat storage the inside temperature during a clear day ranges between 50 and 60° C and humidity of 70-80%, while during the night with outside temperature ranging between -5 to -6° C and wind velocity of 3-4 m/sec, the inside temperature drops to 0° C. Since extreme diurnal changes in temperature inhibit the normal growth of plants, engineers experimented with the solar heat storage to an inside temperature of 9-10° C at night, which was considered more than sufficient for the normal growth of plants [161].

2. Drying of products

A large portion of the world's supply of dried fruits and vegetables continues to be sun-dried in the open under primitive conditions. Being unprotected from unexpected rains, windborne dirt and dust, and from infestation by insects, rodents etc, the quality is seriously degraded, sometimes beyond edibility. Solar dehydration has not yet been fully dealt with by those concerned with solar research [162].

Although drying is one of the oldest uses of solar energy, the proportion of modern solar development activity devoted to this application is comparatively small. There may be several explanations for the limited studies in this field. Where solar drying is practiced, particularly with agricultural crops, simple and crude methods are reasonably effective. The spreading of the crop on the ground or on a platform and drying at directly in the sun is cheaply and successfully employed for many products throughout the world. Practically no capital outlay for equipment is required, and although considerable labor may be involved, this is seldom costly.

Another deterrent is the intermittence of solar energy (extended cloudiness) which can preclude satisfactory and continuous solar drying. Hence if a product must be dried reasonably promptly, auxiliary energy is required for continuous operation.

Recent work in solar drying has been oriented in both directions, i.e., there has been work in direct drying, wherein the product is exposed to solar radiation and by energy absorption plus air circulation, the moisture is evaporated into the atmosphere. In the other system, drying is indirectly accomplished by use of a solar air heater of some type which furnishes hot air to a separate drying unit. In the latter system, other sources of heat could usually be replaced by solar energy in the same general drying facility. However, the design of the drying unit itself, apart from the solar heat supply system, may have features which are specifically adapted to a solar heat source.

Studies have also been devoted to combinations of these two primary types of solar drying systems. Thus a solar collector can be used for providing a supply of hot air to a drying unit in which a product is directly irradiated by solar energy. Another type of solar dryer considered would use a conventional steam-heated dryer of one of several standard types, to which steam is supplied from a solar boiler [75]. The drying may be speeded up and better controlled by flat-plate solar collectors. In addition, mirror-type collectors can be used for drying (evaporation), as done in Burma and India for concentrating palm juice to produce joggery (unrefined sugar), thereby avoiding transportation costs and unwanted fermentation. Such a simple mirror concentrator is estimated to pay for itself in three seasons. The economic feasibility of more controlled solar drying, as compared with simple direct drying, may be justified by higher quality, cleanliness, time saving, reduced spoilage and other factors. But it may also have to be justified

in comparison with electrical or fuel heating drying, which can achieve the same and often better results or in terms of fuel and power savings in combined operations.

Simple direct drying, which now has been studied in some of its scientific aspects, has still been found to be the best, especially in countries lacking natural resources or electric power [3]. In Australia, considerable results have been obtained in sun drying of grapes properly arranged on drying racks, constructed from tiers of wire netting stretched between steel posts. The racks measure 50 m long, 1.25 m wide, and 2.4 m high and are covered by an iron roof 2.5 m wide; they are aligned in a north-south direction. The vertical tiered rack, which has been developed by the Australian dried fruit industry and which operates partly by the absorption of direct solar radiation and partly by natural air circulation (see Chapter III, B-1) provides a less expensive and more effective system of drying than by complicated solar energy absorbers and a supplementary source of power. While this method depends on good weather, the same limitation applies to other solar devices, which would be far less efficient and a great deal more expensive to operate under unseasonal conditions.

The performance of the tiered drying racks was also compared with that of two types of artificial dryers employing solar absorbers to heat the air. In one system, the grapes were dried in a closed insulated chamber heated by an internal solar energy absorber made of sheet metal fins under a single layer of glass. In this dryer, the temperature exceeded 15° C above

the ambient temperature and the average thermal efficiency was 50 percent. However, the grapes dried more slowly than those exposed on tiered racks under identical conditions, and the quality of the final product was very poor.

This result prompted experiments with a second type of dryer in which a large volume of air was preheated in a simple solar absorber made of jute fabric. As a result of initial tests, a large-scale unit capable of heating air at a rate of 330 $m^3$/min. was installed alongside of a drying rack which was covered with plastic sheet to form a drying chamber. This type of absorber heated the air 5-8$^\circ$ C above the ambient temperature, and the thermal efficiency of the absorber was 50 percent. The rate of drying was similar to that observed on the open tiered racks under the same conditions, but the quality of the product was not as good.

With minor modifications, the system of tiered racks may prove to be well suited to the drying of other agricultural crops. The idea of using a stack of horizontal surfaces as a solar energy absorber may have other applications, particularly in high latitudes where the low angle of the sun precludes the use of other types of solar energy absorbers [72].

A new possible application is seen in direct solar drying of oil shale in Brazil. Oil shale mined in the Paraiba Valley has a high moisture content, averaging about 33 percent. The subsequent processing of this mineral for liquid fuel production requires high-temperature thermal

decomposition of the hydrocarbons in the shale, called retorting. Heat for this process is usually provided by combustion of a portion of the organic material in the shale. It is obvious that the moisture requires heat for its vaporization and that if a dry shale were supplied to the retorting process, a greater net yield of liquid and gaseous hydrocarbons could be obtained. Solar drying of the shale prior to retorting was therefore considered as a means for increasing the efficiency of shale oil recovery. It has been estimated that the cost (mostly material handling) by solar drying is about one-third of the resulting increase in product value and the final result is far superior to fuel-heated drying of the shale prior to retorting.

The very low value of a ton of oil shale precludes any substantial expenditure for drying it. The method therefore considered potentially useful requires the spreading of crushed wet shale on a large area of ground, allowing it to dry in the sun until the moisture content has been sufficiently reduced, and then collecting the dried shale for further processing. Machinery would be employed in a commercial plant to handle the thousands of tons considered a minimum practical daily output [75].

Use of solar energy to heat forced natural air for crop drying has been adopted in a few cases. Research investigations by agricultural engineers of USDA and several agricultural experimental stations have produced important design criteria. The practicability of using solar energy in this manner is confined at present to "in storage" use where rapid drying and large reductions in moisture content are necessary.

There are three general methods and capacities of forced air drying: drying with heated air (150-180° F), drying with unheated (ambient) air, and drying with supplementary heated air (5-20° F temperature rise above ambient air conditions). Conventional systems use a fuel to heat air for drying by heated air (150-180° F) and by supplementary heated air (5-20° F).

In the mid 1930's, investigators of the Tennessee Valley Authority in a preliminary research report considered use of solar energy for hay drying. Collector efficiencies of approximately 20 percent were obtained using air flow approaching 5 cfm/sq ft of absorber. The absorber surface was weathered (oxidized) galvanized sheet metal roofing. The maximum air temperature rise of 25° lowered the relative humidity by 40 percent; the sunshine period average rise of 15° F reduced the relative humidity 20 percent, providing air with an enhanced drying potential.

Air volume reduction of almost 25 percent was observed with the design studied. In this design, air entered at the roof eaves and was subsequently drawn down through a vertical duct from a ridge plenum.

An over-all design should consider the building and the drying system to be employed. The shape and orientation of the building will have its influence on the solar collector as will the type and location of the drying fan. These factors must be considered together and compromises in design minimized.

If the collector is part of a roof surface, air may be introduced at the eaves and removed at the ridge. It could also be introduced at one end of the roof and removed at the other. A third alternative is to place air intakes at both ends of the roof and remove it at the center through a slot in the sheathing. In the latter two cases, additional roof girts will need to be provided for the air flow channel unless a departure is made from conventional roof construction designs.

The design of one system that has been operated during several drying seasons is based on a quonset type sheet metal structure. Air is introduced at the east end of the south-facing side of the building. It is drawn longitudinally through a channel under the entire south side, which is painted black, and is collected in a plenum built into the west end of the building. Heated air in the plenum is picked up by a fan and is forced into a slotted main duct under the center of the stored ear corn. Moisture laden air emerges from the ear corn into the void space between the corn surface and the roof. It is discharged through louvered openings in the end of the building (Fig. 177).

Solar heated air in an alternate design may be drawn down through a slot in the sheathing, distributed over and drawn down through the grain to a floor lateral and main duct system from which the fan exhausts air to the outside. A disadvantage of this type of design is the relatively greater difficulty in observing the grain. The tendency may be for the dryer operator to terminate blower operation before drying is complete. Another

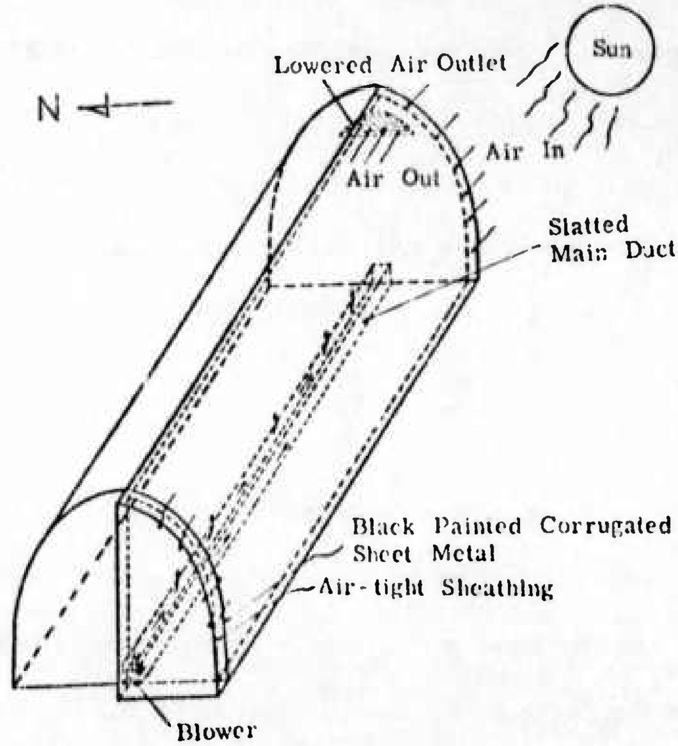


Fig. 177. Schematic of a solar-supplemented forced air drawing system, USA [73].

limitation is the necessity for tight construction. Any air leak on the suction side of the fan may cause short circuiting of the air around the grain and poor system operation.

The length of air path through the solar heater and the necessary air space to keep air pressure drops to the desirable 0.1 inch of water may be reduced by introducing air at both ends of the building or alternately at the eave of the building (for long buildings).

Fall season grain drying has been conducted in experimental 125 bu triangular shaped drying bins (Fig. 178). This shape provided a wall well oriented for fall drying conditions, as well as a satisfactory collector area to bin volume ratio.

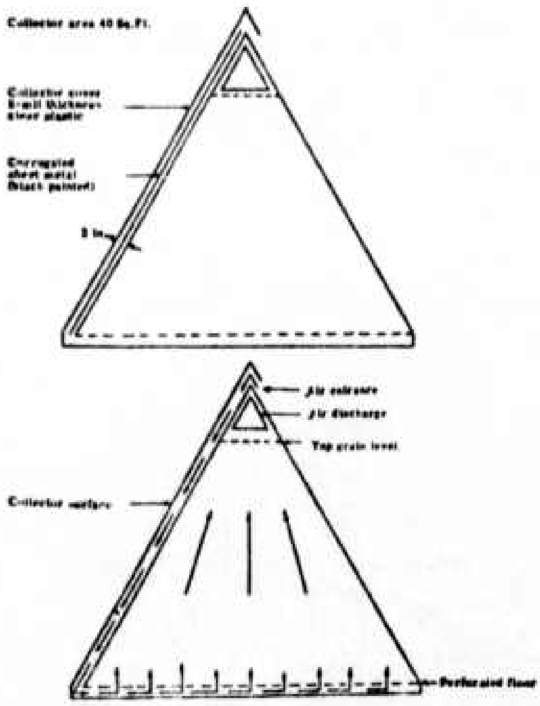


Fig. 178. Schematic of triangular shaped drying bins, USA [73].

The collector design used was black-painted corrugated sheet metal suspended at mid-depth of the 2 x 4 inch external framing. Air was drawn down from the peak (apex) over both surfaces of the absorber and introduced under the drying grain.

The transparent plastic film used over the absorber was of solar resistant 3 mil (.003 inch) polyester.

Two air flows (of 6 and 12 cfm/sq ft of net collector area) were used during successive fall seasons, providing an air flow of approximately 2 and 4 cfm/bu of the drying grain. Grain sorghum and corn were used, respectively, in the successive fall periods with initial moisture content of 17.5 to 18 percent [73].

A typical solar grain drying and storage building (Fig. 179) was

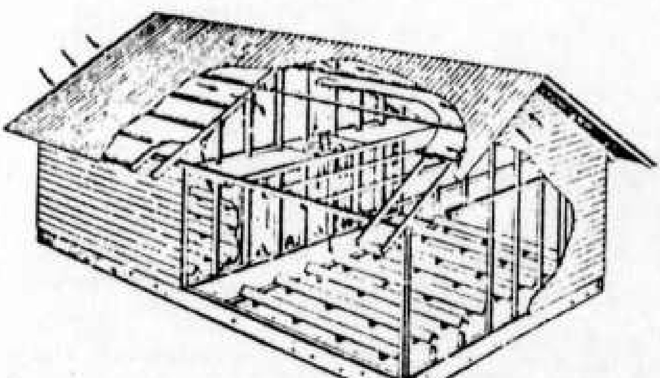

Fig. 179. Drawing of a typical solar grain drying and storage building, USA [74].

designed so that the air will move up through the grain, and has a drying bin on each side of the air duct. Each bin will hold about 1000 $ft^3$ of grain when filled to a depth of five feet. Only one-half of the roof is used for heating air. The system is designed to dry one bin at a time, but in an emergency both bins could be supplied with air at the same time. The air enters the

roof at the ends of the building, moves toward the center section and into the upper plenum chamber. The air is then forced into the lower chamber by a blower, from where it moves through the lateral ducts and the grain. The moist air leaves the bins through openings at the gables or in the north roof. In this type of solar heating, a flat plate with air passing below is essential, which requires the roof to be made of glass and absorbing plate. In some cases metal roofing may be used for the absorbing surface as well as for the roof of the crop drying building.

Experience indicates that the addition of a solar air heater to an unheated air crop drying system will reduce drying time 50 to 75 percent. On some days, it will be possible to dry a crop with solar heated air instead of with unheated air because of high outside relative humidity. The economics in each situation will depend on the quantity of crop dried and weather conditions. It has been estimated that the added cost of a solar drying system will be recovered in one to five years' time [74].

Researchers from the Department of Mechanical Engineering Middle East Technical University, Ankara, Turkey have designed a prototype solar fruit and vegetable drier (Fig. 180). This unit comprises a glass-covered flat plate collector containing metal chips (heat absorbent), a dryer with translucent walls, and an insulated tunnel connecting the collector with the dryer. The quality of the dried products as well as the drying time were found favorable for the solar dryer as compared with open-air drying.

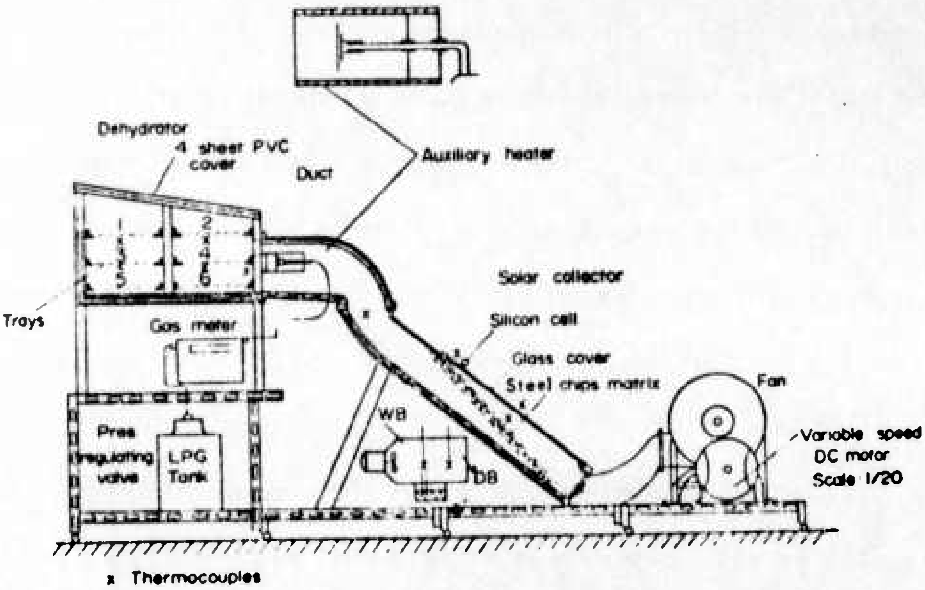


Fig. 180. Schematic of a solar fruit and vegetable dryer, Turkey [162].

In addition, an economic analysis has been undertaken to investigate the possibility of using various heat sources for an auxiliary heating system. Such a system is being developed and will be coupled to the prototype solar drier to enable all-weather operation.

In selecting a solar collector, several researchers have studied the performance of perforated or slit-and-expanded types of collectors. Emphasizing the necessity of operating at low matrix surface temperatures in order to decrease collector heat losses, M. Akyurt and M. K. Selçuk [162]

maintain that matrices which receive solar radiation "in depth" exhibit the highest efficiencies. Prior to designing the solar collector, they made a survey of some potential collector material with respect to cost, availability, and thermal characteristics. The results of absorptivity measurements are tabulated below:

Absorptivities of various materials at 50°C

| Material | Absorptivity | Material | Absorptivity |
|---|---|---|---|
| Coal slag | 0·60 | Steel chips | 0·97 |
| Sheep wool (white) | 0·19 | Steel chips (rusty) | 0·70 |
| Paper (white) | 0·39 | Aluminum chips | 0·28 |
| Concrete (rough surface) | 0·25 | Copper chips | 0·22 |
| Dry quince leaves | 0·06 | Bims* | 0·32 |
| Cut wheat straw | 0·13 | | |

*Local construction material made of white chalk.

For this solar dryer, steel chips were chosen for the solar collector matrix as they are readily and cheaply available, exhibit a high heat transfer area per unit volume, and have very high absorptivity.

The collector, with a net collection area of 1 $m^2$, consisting of a single black-printed matrix,is fitted into a wooden frame with insulated side walls and bottom. The air, entering the collector either by free convection or forced in by a variable-speed blower, has to traverse the packed pillow (matrix) thereby cooling it. The heated air then flows along a mixing chamber, a part of which serves as the insulated tunnel between the collector and the dehydrator.

The dryer has translucent east and west walls and roof which consists of 4 layers of polyvinyl chloride sheets separated by air gaps. Besides providing good insulation, the exposure of drying goods to undesirably high direct radiation intensities was thus prevented, although enough radiation was transmitted (75% of incident radiation) for full color development. Shelves of plastic covered with wire mesh were designed for protection against sulfur dioxide ($SO_2$) corrosion.

Thermocouples were located at several points in and around the assembly for determining wet and dry bulb temperatures. A calibrated silicon cell was used to measure incident solar radiation, and an orifice meter measured the air flow rate.

A novel feature of this dryer is the incorporation of an auxiliary heating system parallel to the solar collector, to supplement the latter when necessary in drying operations [162]

The State Pedagogical Institute in Karshi, Uzbek SSR, has designed and tested a combination greenhouse-dryer type model (Fig. 181). This model, in use at the "Aurora" State Farm in Karshi Oblast, has an area of 850 $m^2$. During five years of tests, it has been established that the inside temperature was relatively constant even during brief drops in ambient temperature (to (-) 20$^\circ$ C), and fluctuates only over about 1.5-2$^\circ$ C. The maximum inside temperature of 35$^\circ$ C was observed for most of the time.

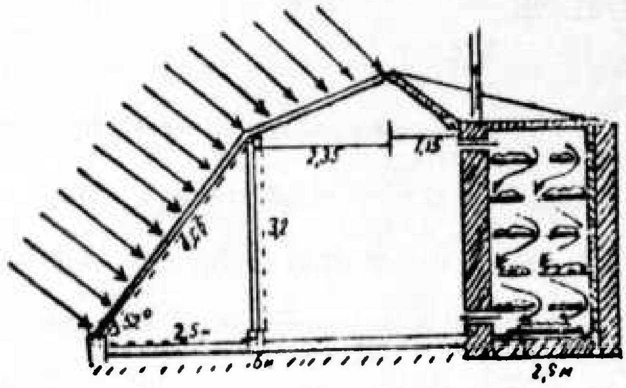

Fig. 181. Section of a combined solar greenhouse-dryer unit (dimensions in m), USSR [163].

Because of partial accumulation of the daily solar radiation, this model can maintain an elevated temperature during the whole season without auxiliary heating. During autumn however, harmful temperatures develop inside the unit requiring artificial ventilation.

It was concluded that this unit has variable temperatures, but is still favorable for growing plants and drying of agricultural products. It is therefore proposed that they operate without auxiliary heating in Karshi Oblast and regions with similar climatic conditions [163].

In general, it is felt that while more research in collector design remains to be accomplished, work has progressed to the point that various satisfactory designs can be produced with further field research to obtain dried products with exceptional quality, appearance, and nutritive values.

## 3. Seed Irradiation

Seeds of many species have light-sensitive germination responses controlled by the plant pigment phytochrome. A brief exposure to red or far-infrared radiant energy may enable or inhibit subsequent germination when all other environmental factors are favorable for germination. When parent plants are grown under white light containing markedly different proportions of red and far-infrared energy, the seeds harvested have altered germination responses. For example, seed produced under light energy rich in wavelengths greater than 700 mμ is most sensitive to subsequent red induction. Seed produced under light of wavelengths less than 700 mμ requires up to $10^4$ times as much energy to achieve the same percent level of germination. Research supports the conclusion that phytochrome in the parent plant is involved in regulating the sensitivity to subsequent light exposures.

One of the persistent problems of research in photoperiodic timing phenomena for biological systems is to discover the exact environmental cue from solar radiation by which plants and animals measure the length of the day. In any case, it seems apparent that the level of phytochrome maintained during the light cycle can regulate the subsequent sensitivity and germination pattern of seeds. Similarly, it is known that the quality of the end of the day radiation is important for growth and development of plants. Such responses as internode length, pigment content, leaf thickness and the concentrations of various metabolitics can be considerably affected by red or

far-infrared exposure at the end of the day. The observed rapid shift to far-infrared/red shortly before sunset may also be important for these responses.

Only in the last two decades has concentrated sunlight been used systematically in medicine, biology, and chemistry. However, during this short time the multitherapeutic effects of concentrated sunlight in the treatment of a number of diseases has been established; for example a stimulating effect on the growth and development of chicks when the eggs are irradiated before incubation has been noted. In seed growing, concentrated sunlight can be an effective means of combating various insects, pests and fungal diseases.

Soviet scientists apparently for the first time used concentrated sunlight during phytophysiological investigations in the Arctic (1959-1962) on the irradiation of seeds before sowing, and subsequently on barley and wheat plants at various stages of development.

During the same years V. N. Bukhman and V. A. Miroshnichenko carried out similar investigations on seed corn at Alma-Ata, Kazakh SSR.

In all these experiments, the sunlight was concentrated by a faceted reflector of the Bukhman* type (Fig. 182). The effective area of this

* V. N. Bukhman, a pioneer of Soviet experimental solar engineering and designer of several types of solar concentrators.

Fig. 182. Solar reflector of the Bukhman type used for irradiation of seeds before sowing, USSR [165].

reflector was 3 $m^2$ and the intensity of the reflected light flux was on the average 10-12 times greater than that of direct sunlight.

To avoid burning of seeds and plants, the reflector was oscillated during irradiation with concentrated solar pulses at a rate of 120-150 times a minute. From these Arctic studies, it has been concluded that the pulsed irradiation of seeds for 20-60 minutes before sowing had a favorable effect on the germination rate, number of productive bushes, growth,

development, and yield of the plants. In addition, plants grown from irradiated seeds have better pigmentation, absorb radiant energy more intensely over the entire spectrum, and photosynthesize more vigorously than standard plants (by 20% when irradiated for 60 minutes, and by 40% when irradiated for 30 minutes). The irradiated seeds produced plants with grains heavier and larger than those of plants from non-irradiated seeds; they also developed earlier and showed more rapid growth rates.

Additional irradiation of barley plants by solar concentrated pulses during the period fromthe start of the sprouting stage to the onset of heading (85 minutes for a "soft" dose and up to 180 minutes for a "hard" dose) had an effect on pigment synthesis, absorption of radiant energy, photosynthesis, and plant development. However, irradiation with a "soft" dose enhanced the photophilic tendencies of the plant, resulting in better utilization of radiant energy and consequently in a greater grain yield.

Results obtained on pre-sowing irradiation of seeds in the Arctic stimulated investigations in other climatic zones of the USSR. On the initiative of B. V. Petukhov, at the end of 1961 a special subcommittee for the coordination of research for the use of concentrated sunlight in agriculture was set up under the Solar Power Section of the State Committee of the RSFSR Council of Ministers for the Coordination of Research. Investigations into the effects of solar concentration on seeds, plants, and animals have since been launched in Kazakhstan, Moldavia, Ukraine, as well

as the far North. Many experiments have confirmed the stimulating effect of the pre-sowing irradiation of seeds of various cultivated plants (cereals, oil-producing plants, legumes, vegetables, and others) on quality, yield, and early ripening.

In research work in the Moldavian SSR, an all-metal reflector made of electropolished aluminum was also used (Fig. 183) for concentration

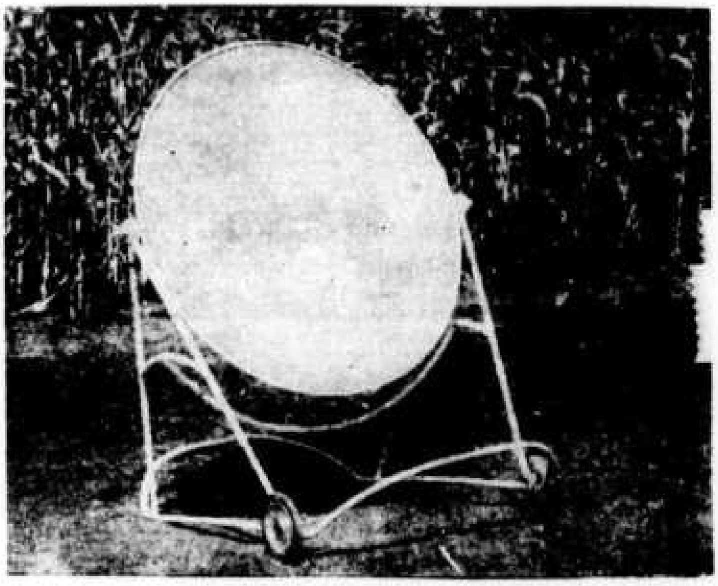

Fig. 183. All-metal reflector made of electropolished aluminum, USSR [165].

of radiant energy at various wavelengths. Dry and water-soaked (for 24 hr) seeds were exposed to the complete solar spectrum, and without the infrared, for 5, 10, 15, 20 and 30 minutes in a centrifuge rotated at 80 rpm. In the second variant of seed irradiation, the infrared region of the spectrum was

cut off by a liquid copper sulfate light filter, 10 cm thick. The seeds were irradiated at noontime at an integral direct solar radiation flux of 1.1 to 1.2 $cal/cm^2/min$; the temperature did not exceed 45-50° C. Depending on the duration of irradiation, a discrete form of shrinking of the seeds was observed. When irradiated, the seeds of different plants yield their water differently, especially during the initial period of irradiation; but even after 30 minutes irradiation the yield of water did not exceed 5.0 to 5.7% of the initial seed weight.

In an experiment on a specific variety of corn it was established that pre-sowing irradiation of seeds with the total solar spectrum as well as without the infrared increased the field germination rate by 14-15% in comparison with the standard, stimulated growth and development of the plants, and augmented the organic mass and grain, while shortening the growing season by 5-6 days.

In general, the leaf area of the experimental plants at the tasseling stage was 9-11% (fresh and dry weights 10-18%) greater than for the standard plants. Similar results were obtained for a sunflower variety. As a result of pre-sowing irradiation of fodder peas, the increase in the yield of organic mass was about 6-10% and in the yield of peas, 5-8%.

It seems probable that the stimulating effect of concentrated sunshine irradiation is originated mainly in the visible (photo effect) and not in the infrared (thermal effect) portion of the spectrum. The use of concentrated sunlight for pre-sowing irradiation of seeds of a number of crop plants, tubers, and vegetable plants is quite promising and of general biological interest [165].

Laboratory experiments have also produced favorable results showing that irradiation by concentrated solar pulses raises the germination capacity of cotton seed by 13 percent and rice by 29 percent as compared with untreated seeds. Irradiation increases the sprouting energy of the seed, and positive results have been registered after an irradiation dose of 30 minutes. Soaking of seeds in irradiated chlorella (which acts as biostimulant) suspension with a density of 60 million cells per milliliter also stimulates germination.

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